A LABORATORY MANUAL OF PHYSICS

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FOR USE IN HIGH SCHOOLS

BY

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PREFACE

Our special objects in the preparation of this volume may be very simply stated. They are as follows: —

1. We have aimed not to describe classical experiments, but to illustrate the first principles of physics. The simplicity with which this can be done is to us a matter of constant surprise and delight.

2. Our purpose has been to supplement some of the excellent text-books already in use, most of which, however, were prepared with especial reference to the class-room rather than to the laboratory.

It will be observed that, almost without exception, the principles which we have sought to illustrate are discussed in each of the seven volumes to which we make reference.

3. One of our main objects has been to reduce to a minimum the expenditure of teaching energy. With this in mind we have placed a list of apparatus at the beginning of each exercise enabling the instructor to prepare quickly and confidently the entire outfit necessary for the experiment. To this end also we have made a special effort to state the "problem," not by merely giving the name of some instrument, but by stating the controlling principle and the point of view from which the entire experiment should be worked out.

Economy of teaching energy has also led us to suggest only apparatus which is simple, inexpensive, easily obtained, and easily duplicated. At the same time we have borne in mind the fact that apparatus is not necessarily simple because it is home-made. Indeed, apparatus can be considered cheap only when it combines economy of first cost with economy of thought on the part of the student and economy of energy on the part of the instructor.

4. We have endeavored to present a series of laboratory directions which in thought and method are so welded together as to form a continuous and homogeneous whole; and yet to make each exercise so self-contained that the scholarly teacher may select, say, thirty or sixty out of a list of more than ninety exercises, without calling upon the student to make any cross-references and without any serious break in the continuity of the subject.

5. We have tried to avoid the excessive use of blanks for the student to fill out with mechanically obtained data, and yet to introduce, *in the earlier pages*, a number of blanks sufficient to serve as a pattern for clear and concise records.

We gladly acknowledge our indebtedness to Professor A. B. Porter of the Armour Institute for a large number of scholarly and practicable suggestions, some of which are embodied in almost every exercise.

We take pleasure in thanking also Professor B. W. Snow, of the University of Wisconsin, Mr. W. F. Minium, graduate student at the University of California, Mr. F. J. Truby, of the Northwestern Academy, and Miss Caroline L. Crew, of Wilmington, Delaware, for able and helpful criticisms of the manuscript.

Any suggestions as to how these experiments may be more simply performed or more clearly and correctly described, will be very gratefully received.

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EVANSTON, ILLINOIS,
November 19, 1901.

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NOTE ON THE SELECTION OF EXPERIMENTS

The equipment of any laboratory must determine to a large extent the group of experiments best adapted for use in that laboratory.

The two following lists of exercises are designed partly to preserve due proportion between the various parts of the subject and partly to consult economy of equipment.

For a course where the school programme admits of only thirty laboratory periods a year, the following list is suggested:—

Exercises.—3, 5, 10, 12, 20, 25, 26, 27, 28, 30, 35, 37, 39, 42, 48, 50, 52, 57, 61, 63, 67, 71, 72, 74, 75, 84, 85, 86, 90, 94.

For a course in which the programme admits of sixty laboratory periods a year, the following list is suggested in addition to that just given:—

Exercises.—1, 4, 16, 17, 18, 19, 22, 23, 33, 36, 38, 40, 41, 44, 46, 51, 54, 58, 60, 64, 69, 73, 76, 77, 81, 82, 83, 87, 89, 92.

In this Manual, reference is made to the latest editions of the following text-books:—

Avery, *School Physics* (1901).

Carhart and Chute, *Elements of Physics* (1901).

Crew, *Elements of Physics*, 1900.

Gage, *Elements of Physics*, 1899.

Hall and Bergen, *Text-book of Physics*, 1897.

Rowland and Ames, *Elements of Physics*, 1899.

Wentworth and Hill, *Text-book of Physics*, 1901.

For the sake of brevity, we shall cite the name of the author only and omit the title of the book. Numbers refer to *articles* unless otherwise stated.

A LABORATORY MANUAL OF PHYSICS

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CHAPTER I

SOME PRELIMINARY EXPERIMENTS

Exercise 1. — Comparison of Lengths

Apparatus. — Two metre sticks. Use the ordinary maple metre sticks, graduated in centimetres and millimetres on one side, and in inches on the other.

Problem. — To find the length of an inch, in centimetres, by directly comparing a length of several inches with the corresponding length on a scale of centimetres.

Experiment. — (*a*) Select for comparison a space of three inches on one of the inch scales. On many metre sticks the lines are too deep and wide for use in accurate work. Choose lines as sharp and distinct as possible.

Lay the metre sticks on the table, placing the chosen space of three inches in contact with the metric scale on the other stick. Do this entirely *at random; i.e.* do not try to make any of the lines coincide. To do so would be troublesome and no more accurate.

Caution. — Do not make lead-pencil or other marks on the metre sticks. If you cannot remember which lines you are using, record their numbers in your note-book. *Never do anything which tends to disfigure a piece of apparatus.*

Read off and record the position on the metric scale, which is indicated by the line at one end of your three-inch space. Usually this end-line will not coincide with any one of the millimetre marks. It will thus be necessary to *estimate* its

position to a tenth of a millimetre. Read off in the same way the position of the other end of your three-inch space.

(*b*). Subtract the smaller of the readings found in (*a*) from the greater. The difference will be the length of three inches, expressed in centimetres.

(*c*) Repeat (*a*) and (*b*), making in all four determinations with a length of three inches. The position of the metre sticks should be changed for each new determination.

(*d*) Repeat the above with lengths of four, five, and six inches, successively, using each length four times. This will make 16 separate determinations of the length of an inch. Place your results in the following form:

Number of observation	Number of inches compared	Reading of first end	Reading of second end	Difference	Length of 1 inch in centimetres
		cm.	cm.	cm.	
1	2	31.35	26.29	5.06	2.530
2	2	44.50	39.43	5.07	2.535
3	2	63.32	58.26	5.06	2.530
etc.					

Mean =

At the foot of the last column write the average, or mean, of the 16 determinations, and consider this your value of the length of an inch in centimetres.

Why is it better to make several determinations of the length of an inch? Is any single measurement likely to be absolutely exact? The scale may be unequally divided. Accidental errors in readings may be made. Why not compare a single inch, instead of a space of several inches?

ESTIMATION OF FRACTIONAL PARTS

In making measurements with a divided scale, the line or point to which we measure does not usually coincide with any of the marks of the scale, but falls between two of them.

In Fig. 1, for example, the line *A* lies beyond the 21 cm. mark, but falls short of the 22 cm. mark. Here we might call the reading

21 cm., as this is the next lowest whole centimetre. But it is more accurate to *estimate* by the eye the number of *tenths* of a division by which the position of A exceeds 21 cm. In the present case, it will be seen that A lies about $\frac{4}{5}$, or 0.8, of a division beyond 21 cm. Hence the whole estimated reading is 21.8 cm.

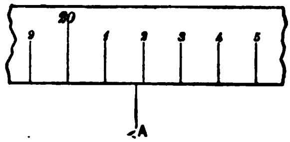

Fig. 1.

It is not to be supposed, however, that a reading so obtained is absolutely correct. One may easily make a mistake of one or two tenths of a division. Yet if we make no attempt to read closer than the nearest whole division, the error will frequently amount to three or four, or even five, tenths of a division.

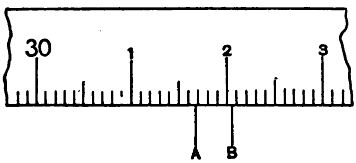

Fig. 2.

In making readings on a scale of centimetres and millimetres, read first the number of whole centimetres; then read the additional millimetres, calling these *tenths* of a centimetre. After this, estimate the number of tenths of a millimetre, calling these *hundredths* of a centimetre. The fraction thus obtained should always be written *decimally*. Thus, in Fig. 2, we have for the line A,

Number of whole centimetres, 31	31.	cm.
Number of whole millimetres, 6	0.6	"
Number of tenths of millimetres (estimated), 8 . .	0.08	"
Giving, for the complete reading	31.68	cm.

Similarly, the reading at B is $32 + 0.0 + 0.05 = 32.05$ cm.

The student should record in his notes the complete reading only, as he will soon learn to go through the above process of addition mentally.

Exercise 2. — To represent Directed Quantities by Means of Straight Lines drawn on Paper

References. — Crew, 5; Carhart and Chute, 45–48; Rowland and Ames, 15–17; Hall and Bergen, 241–242.

Apparatus. — A pencil compass; sheet of paper; sharp lead pencil.

Problem. — To distinguish between scalar and vector quantities.

Experiment. — (*a*) The shore line of a lake runs due north and south. A steamer starts from a point *A* on the lake shore, and travels in a straight line for 3 hours at the rate of 10 miles per hour.

Can you locate the position of the steamer at the end of 3 hours? How far from the point *A* will the steamer be at the end of 3 hours? Make a small chart, drawing upon it the coast line, and the point *A*. Next draw upon this chart all the possible positions which this steamer might have after having steamed for three hours in a straight line at the rate of 10 miles per hour. In drawing this curve, use a scale of 5 miles to the centimetre, that is, represent the distance 30 miles by a length of 6 centimetres.

(*b*) Imagine the steamer to have sailed *in a northeast direction* for 3 hours at the rate of 10 miles an hour. Locate the position of the vessel on your chart. Call the point at which the vessel is located *B*. Is this line *AB* a vector quantity or a scalar quantity? State the reasons for your opinion. The line *AB* defines the position of *B* with respect to a certain point. What point is this?

(*c*) The steamer having sailed 30 miles northeast now changes her course and sails due east for 20 miles. Call her present position, *C*, and locate this position *C* on your chart. The line *BC* defines the position of *C* with respect to what point? How is the position *C* defined with respect to the point *A*? If we call the lines *AB* and *BC* "components," the line *AC* is called a "resultant."

(*d*) Suppose the steamer had first sailed 20 miles east from the point *A*, then at the end of the 20 miles had changed her course and sailed 30 miles northeast. What would have been her position?

(*e*) In your report give two examples of things which can be measured but which have no direction.

Quantities of this kind are said to be **scalar** quantities.

Exercise 3. — Determination of π

Apparatus. — Three circular disks ranging from 2 to 8 inches in diameter. They may be made of wood, glass, brass, cardboard, or sheet-tin. If they are made of wood, they should range from 4 to 8 inches in diameter, and should be about 1 inch thick. A scale divided either in inches or in centimetres.

Problem. — To measure the length of the circumference for each of these three disks; then to measure the diameter of each circle; then to find for each disk the quotient of the number which represents the length of the circumference divided by the number which represents the length of the diameter. This ratio is commonly denoted by π.

Experiment. — (*a*) To measure the circumference make a scratch or pencil mark near the edge of the disk. Stand the

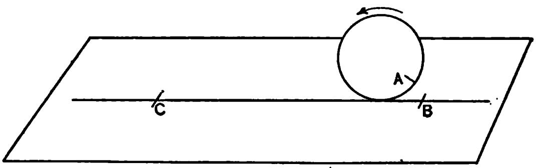

FIG. 3.

disk on edge, and bring this mark, *A*, in Fig. 3, to coincide with some marked point, say *B*, on the table or on a sheet of white paper. Now roll the disk edgewise along a straight line until the mark *A* again comes to the bottom of the disk.

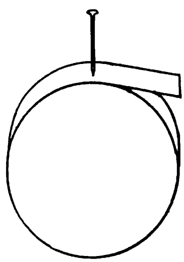

FIG. 4.

Mark this point on the paper and call it *C*, as indicated in Fig. 3. The distance *CB* is the length of the circumference, and can be measured with a scale. Repeat this operation for each of the other disks. How does the wheelwright measure the circumference of a tire or a wheel?

In case you have wooden disks, a better plan is to wrap a strip of smooth tough paper around the

edge of the disk, and then make a pinhole through the overlapping edges of the paper, as indicated in Fig. 4.

The distance between the two holes thus produced in the paper is the length of the circumference.

(*b*) With a lead pencil draw three diameters across the side of the disk. Measure each of these three diameters, using the same scale that you used before. The average value of these three measurements you may call the diameter of this disk. Repeat this operation for each of the other two disks.

(*c*) Collect your results in a table such as the following:

Disk	Diameter in cm.				Circumference in cm.	$\frac{\text{Circumference}}{\text{Diameter}}$
	Observation			Mean		
	1	2	3			
First						
Second						
Third						

Compute the ratio indicated in the last column. You will observe that the numbers in this column have nearly the same value. This ratio (which is generally called π) is, therefore, said to be a **constant**.

If the diameter of a circle were increased to five times its present size, what change would be produced in the length of its circumference? If you measured a number of other circles, do you think the ratio of the circumference to the diameter would be practically the same as you have found it above?

Variation of One Quantity with Another

When two quantities change in such a way that their ratio is a constant, one of those quantities is said to vary directly as the other. Thus, in circles, the length of the circumference is said to vary directly as the diameter.

Exercise 4. — Measurement of Angles

Reference. — Crew, *Elements of Physics*, Art. 10.

Apparatus. — Sheet of cardboard; pencil compasses; millimetre scale; sharp pencil.

Problem. — To learn how to measure angles in radians; and to lay off an angle of one radian.

Experiment. — (*a*) On the cardboard draw a circle 4 or 5 inches in diameter. With a pair of shears cut out the circle. Using a little care, you will be able to follow the circumference quite accurately.

With a sharp pencil draw three diameters. These may be about as shown in Fig. 5. You are now to measure, in radians, the angles *AOB*, *AOC*, *AOD*, *AOE*, *AOF*, and finally the whole circle. Note that the angles are to be taken in such a way that each is larger than the preceding.

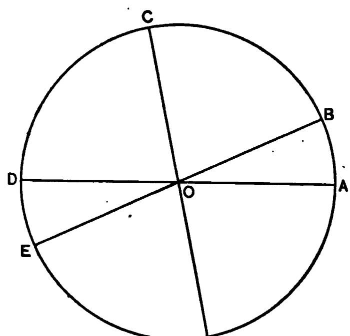

Fig. 5.

(*b*) Proceed to find the length of the radius. Measure the diameter of your circle in at least three directions, estimating tenths of a millimetre. The average of these measurements you may take as the diameter. One-half of this may be taken as the radius.

(*c*) Proceed to find the length of arc of each angle. Begin with the angle *AOB*. Roll the circle along a straight line drawn on paper, as in Exercise 3 (*a*). Mark the points at which *A* and *B* touch this line. Measure the distance between the marks with a millimetre scale. This distance will be the length of the arc *AB*. Do the same for each of the five remaining angles. Record all your measurements in tabular form, as indicated below.

(*d*) In a circle whose radius is 2.5 cm., what is the value in radians of an angle whose arc measures 2.5 cm.? In a circle of radius 4 cm., what angle is subtended by an arc of 8 cm.? What general rule can be given for finding the number of radians in an angle, when the length of its arc and the length of the radius are known? Before attempting to answer this question, read carefully Art. 10 of Crew's *Elements of Physics.*

Calculate the number of radians in each of the six angles whose arcs you have measured.

(*e*) Since the circumference of a circle is $2\pi r$, where r is the radius, find how many times the radius of a circle is contained in its circumference. How many radians are there in a whole circle? How many radians in a semicircle? How many radians do you find in the semicircle *ABCD*? How many in the semicircle *BCDE*? Find this by subtracting angle *AOB* from angle *AOE*. How many in the semicircle *CDEF*?

(*f*) Lay off on paper a straight line equal to the radius of your circle. Roll the circle on this line, and mark off an arc equal in length to the radius. Hence construct an angle equal to one radian. Cut this out, mark it "One radian," and preserve it in your note-book.

Average length of radius = cm.

Angle	Length of arc in cm.	Angle in radians
AOB *AOC* *AOD* etc.		

Exercise 5. — To make a Vernier Caliper

Apparatus. — A piece of thin cardboard or thick paper about 8 inches long and 3 inches wide; millimetre scale. A short piece of a metre stick may be used, but a 20-cm. steel scale is much better. Pair of shears.

Problem. — In Exercise 1 you have *estimated* fractional parts of the smallest division on your metric scale. You are now to learn a method of *measuring* tenths of the smallest scale division, without estimating them.

Experiment. — (*a*) Along the middle of the card draw a straight line, *AB*. (See Fig. 6.) Beginning at a point about 2 cm. from the left end of the card, lay off along *AB* a scale of centimetres. To do this, stand the scale on edge, so that the marks are brought down to the surface of the card.

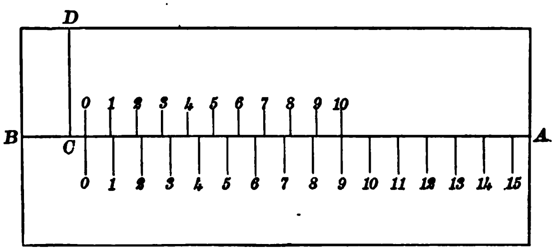

Fig. 6. — Method of making vernier caliper.

Place one of the centimetre marks of the scale at the starting-point. Mark a fine dot with a *sharp* pencil opposite each succeeding centimetre mark, until you have laid off a scale 15 cm. long. During this process the steel scale must not be moved in the least. Choose a level place on the table, so that the scale will stand on edge without being held. Place the scale carefully in the proper position, and *do not touch it* until all the dots have been made.

In making the dots, sight along the marks of the scale vertically. Do not view them from the side. See that each dot is accurately in line with the mark on the scale. Through each dot draw a short line at right angles to *AB*, and number them as in Figs. 6 and 7.

On the other side of the line *AB* lay off in the same way a scale of 10 divisions, *each division being 9 mm. long.* This scale must begin at the same point as the scale of centimetres,

i.e. their zero marks must coincide. The line marked "10" on the new scale will then be found to coincide with the line marked "9" on the centimetre scale. This new scale is called a **vernier.**

(*b*) With shears, cut from *A* to *C* and from *D* to *C*. Do this with care, making the edges of the cut smooth. The card is thus divided into two pieces, as shown in Fig. 7. By sliding the vernier along the centimetre scale, you will form a gap

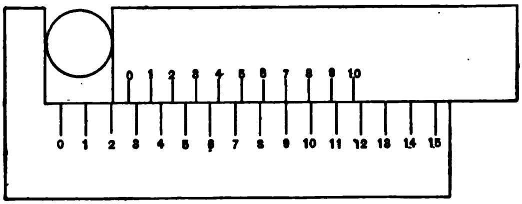

FIG. 7. — A vernier caliper.

between the edges which formerly met along the line *CD*. The diameter of a round object may be measured by inserting it in this gap. Such an instrument is called a **vernier caliper.** The two sides of the gap are called the **jaws** of the caliper.

(*c*) Set the jaws 1 cm. apart. How far must the two zero marks be separated in order to do this? Evidently the distance between the jaws is always the same as the distance between the zero marks.

When the jaws are closed, what is the distance between the 1-mark of the vernier and the 1-mark of the scale? How will you know when the jaws are 0.1 cm. apart?

(*d*) For practice, set the jaws at the following widths: 2 cm.; 0.2 cm.; 0.5 cm.; 1.6 cm.; 4.9 cm. Before proceeding, submit the last setting to your instructor for criticism.

(*e*) Measure with your calipers the diameters of several coins, buttons, or other cylindrical objects. Enter your results in a table, such as the one given below:

Observation	Name of object measured	Diameter in cm.
1 2... etc.		

Exercise 6. — Use of Vernier Caliper

Apparatus. — A pair of slide calipers as indicated in Fig. 8; thread; cylinder, preferably of glass or metal; a metre stick.

Problem. — To learn the use of the vernier caliper, and in particular to measure the diameter of a cylinder.

Experiment. — (*a*) The principle of this caliper is exactly the same as that of the pasteboard caliper made in the preceding exercise. The sliding part is called the **vernier**, the fixed part the **scale**. Bring the two jaws together and note whether the "0" division on the vernier coincides with the "0" division on the scale. If these do not coincide, what correction will have to be made in any result you may obtain with this caliper?

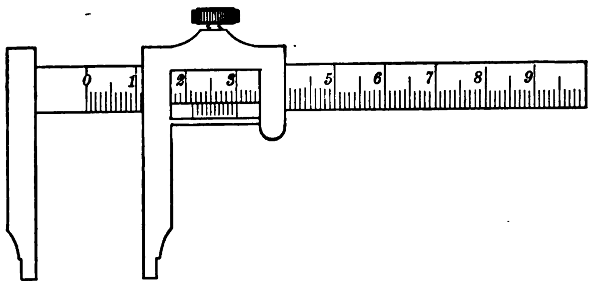

FIG. 8.

While the jaws are together, note how many divisions on the scale are equal to the divided (ruled) portion of the vernier. Record in your report the length of one division of the vernier.

Starting with the jaws together, how far apart will you have to move them in order to make the first division on the vernier

coincide with the first division on the scale? Report this distance to your instructor before proceeding with the rest of this exercise.

(*b*) Measure the diameter of the cylinder in at least three different places. Ask your instructor to verify one of your readings before recording them.

(*c*) Set the two zero divisions (the one on the scale, the other on the vernier) so that they are just 3 mm. apart. How far apart are the jaws of the caliper?

(*d*) Another method of obtaining the diameter of the cylinder when you do not have a pair of calipers is to compute it, having first measured the circumference as follows:

Wrap a thread around the cylinder some four or five times; then take off the thread and measure its length by means of the metre stick. Repeat this operation three times. You will find it convenient to tie a knot near one end of the thread and then to cut the thread, while wrapped about the cylinder, at a point opposite the knot.

Collect your results in a table as follows:

Diameter in cm. (d)	Circumference in cm. (c)	$\frac{c}{d}$	$\pi - \frac{c}{d}$

In order to compute the last column of this table, use the approximate value of π, 3.1416.

Exercise 7. — Use of the Spherometer

Apparatus. — Spherometer, preferably a simple form, such as that indicated in Fig. 9, with a screw of rather large thread, say one millimetre, and with a rather small divided head with the divisions numbered in clockwise order from "0" to "100." Piece of plate glass large enough to hold the spherometer;

microscope slide, cover glass, and small piece of ordinary window glass, as objects to be measured.

Problem. — To learn to measure a short length with great accuracy, and to acquire skill in the use of a screw as a measuring instrument.

Experiment. — The use of the screw for tightening things up is already familiar. When two boards are thus fastened together each turn of the screwdriver brings the head of the screw nearer to the wood. You are familiar also with the use of the bolt; here the screw remains fixed while the nut turns. If the nut is turned in one direction, it is brought nearer the head of the bolt, if it is turned in the opposite direction it is moved away from the head of the bolt. Not only so, but each complete turn of the nut makes it approach the head of the bolt by the *same* amount.

In general a screw works in a nut. Even when a wood screw is put into a board it makes its own nut, else we should not be able to put it in or take it out by means of a screwdriver. The important thing to note is, that whether the nut is turned or the screw is turned through any given angle, the relative position of the nut and the head is changed by the same amount.

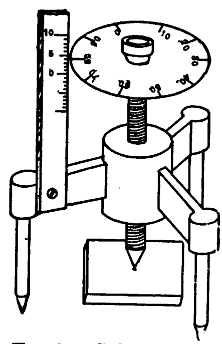

Fig. 9. — Spherometer.

The amount by which the screw moves through the nut for one revolution is called the **pitch of the screw.**

The **spherometer** is merely a screw provided with a nut of a special kind, that is, with one having three feet, and having an upright scale to count the whole number of turns which you give the screw. Not only so, but the head of this spherometer screw is a little different from an ordinary one, for it consists of a circular disk divided generally into fifty or a hundred divisions, so that one can measure not only complete revolutions but also fractions of a revolution.

In order to measure the thickness of any object, say that of a cover glass, proceed as follows:

(*a*) Place the spherometer on a piece of plate glass and turn the screw until its foot just touches the top of the plate glass. If you are careful to see that the screw just touches the plate without lifting either of the other three feet, you will be surprised at the delicacy of your sense of touch. All four feet now lie in one plane, *i.e.* on the surface of the plate glass.

(*b*) Now read the position of the screw in the nut, the whole revolutions being obtained by reading the division, on the upright scale, next below the edge of the divided head. The fractions of a revolution can be read directly from the divided head. This is called the "zero position" or "initial position" of the screw.

What is the pitch of the screw in your spherometer? You can generally determine this by means of a short scale.

By what amount is the screw lifted up when it is turned through one division on the divided head?

(*c*) Next raise the screw by turning, and place underneath it the object whose thickness is to be measured. When the screw is turned down until its point just touches the top of this object, we know that the distance of the screw foot from the top of the plate glass is equal to the thickness of the object. We again read the position of the screw in the nut, as before.

These two readings should be recorded as follows:

	rev.	
Initial position of the screw,	0.45	
Final position of the screw,	3.97	
Hence, thickness of object =	3.52 =	mm.

Make three observations of this kind.

(*d*) Proceed in the same way to measure two other objects. Record your observations and your results in the form of a table.

(*e*) Consider the possibility of dirt on the glass, the possibility of the feet not all lying in one plane when you take

your "zero reading," the possibility of the screw not being exact, and state what you think to be the principal error in the instrument which you are using.

In more advanced work you will learn how this instrument may be used to measure the radius of a spherical surface, and hence, the origin of its name.

Exercise 8. — The Micrometer Caliper

References. — CARHART AND CHUTE, 126; GAGE, 89.

Apparatus. — A micrometer caliper, preferably with ratchet stop, as in Fig. 10; a Brown and Sharpe wire gauge, as in Fig. 11; several short pieces of brass or copper wire, of different sizes, say Nos. 8, 10, 12, 16, 20, and 24. If possible, use a micrometer caliper with a pitch of $\frac{1}{2}$ mm., reading to 0.01 mm.

Problem. — To learn the use of the micrometer caliper; a further study of the screw; in particular, to measure the diameters of several wires with the micrometer caliper, and to find the gauge numbers of the same wires, on a standard wire gauge.

Experiment. — The micrometer caliper, like the spherometer, consists of a screw turning in a nut. From the nut projects a curved arm, at the end of which is a flat polished surface directly opposite the end of the screw, which is also polished; thus forming a pair of parallel jaws. (Note that in the spherometer the jaws are formed by the foot of the screw above, and the piece of plate glass below.)

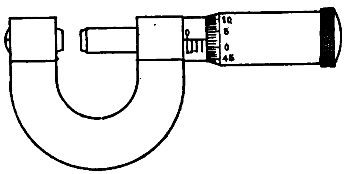

FIG. 10. — A micrometer caliper.

The screw carries a thimble-shaped head, or "cap," partly enclosing the nut. On the edge of this cap are marked fractions of a revolution. Whole revolutions are counted by a scale marked on the nut. The nut is also marked with a line parallel to its axis. This is called the **index**, and serves as a pointer for the divisions on the cap.

(*a*) Open the jaws and find out how many revolutions of the screw correspond to one division of the scale marked on the nut. Hence, by comparing this scale with a scale of centimetres or inches, determine the pitch of the screw. (See the preceding exercise.)

How far are the jaws separated by one revolution of the screw?

Count the number of divisions on the cap. How far are the jaws separated by turning the cap through one of these divisions? What is the smallest fraction of a millimetre that can be measured by *estimating* tenths of a division of the cap?

(*b*) For practice, set the jaws at the following distances: 3.05 mm., 3.56 mm., 3.562 mm. Report the last of these to the instructor for verification.

(*c*) Close the jaws of the caliper. Always do this very gently. Hold the screw head lightly between thumb and finger, so that it will cease to turn at the *first* contact of the jaws with each other, or with an object to be measured. Never force it unnecessarily, else injury to the screw may result. When the jaws are closed, does the zero of the cap coincide with the index? If not, take a reading of its position. This is the **zero-reading**, and must be used to correct all measurements made with the instrument. Make at least three determinations of the zero-reading, and take the mean.

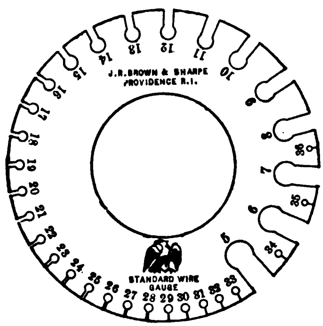

Fig. 11.

(*d*) Measure the diameter of one of the brass wires in at least three places, say near each end and near the middle. Find the mean of these measurements, and correct it as explained in (*c*). This corrected mean may be taken as the diameter of the wire.

(*e*) Take the wire used in (*d*) and try it between the small

parallel jaws of the wire gauge shown in Fig. 11. When you find the smallest space which the wire will enter, the number opposite this space is the gauge number of the wire, according to this wire gauge.

(*f*) Repeat (*d*) and (*e*) with each of the wires given you. Correct your results in a table like the one below.

Mean zero-reading = 0.0005 inch

Obs.	Diameters, as read, in inches				Mean diameter corrected	Gauge number
	1	2	3	Mean		
					inches	
1	.1291	.1295	.1292	.1293	.1288	8
2	.1030	.1025	.1022	.1026	.1021	10
3	.0821	.0825	.0820	.0822	.0817	12

Exercise 9. — Use of Squared Paper for plotting Points

Reference. — Crew, *Elements of Physics*, Art. 2.

Apparatus. — Two sheets of paper ruled in small squares; a sharp lead pencil.

Problem. — To learn how the position of a point in a plane may be represented by two numbers; and, conversely, to locate a point, or series of points, on paper, having given their ordinates and abscissas.

Experiment. — On the paper which is furnished you select two straight lines, one passing horizontally through the middle of the sheet, the other passing vertically through the middle of the sheet. The horizontal line we shall call the **axis of X**; the vertical line is called the **axis of Y**.

Distances measured along the axis of X are called **abscissas,** and are positive when measured toward the right; distances measured along the axis of Y are called **ordinates,** and are positive when measured upward.

(*a*) Plot a point whose abscissa is + 8, and whose ordinate is + 6. What point on the axis of X is chosen as zero from which to measure the abscissas?

(*b*) Plot two points, *A* and *B*, whose positions are as follows:

$$A\begin{cases}\text{abscissa} = +3\\ \text{ordinate} = -10\end{cases} \qquad B\begin{cases}\text{abscissa} = +3\\ \text{ordinate} = +8\end{cases}$$

Submit these three points to your instructor for approval, before proceeding with this work.

(*c*) Taking another sheet of squared paper, select two straight lines, one passing along the left-hand side, the other along the bottom of the sheet. Use these lines as axes of *X* and *Y*, respectively.

Plot the points given in the following table, marking the position of each one with a small fine cross, thus, ×.

Abscissas	Ordinates
+ 4	+ 12
+ 9	+ 18
+ 16	+ 24
+ 25	+ 30
+ 36	+ 36
+ 49	+ 42
+ 64	+ 48
+ 81	+ 54

Join all these points with a fine smooth curve. This curve is simply another way of representing the facts contained in the table. A little later you will be able to tell, by looking at a curve such as this, a great deal about the manner in which the ordinates depend upon the abscissas.

(*d*) Make a table, similar to that given under (*c*), in which each ordinate is twice as large as its abscissa. Choose for abscissas any numbers you like, say the natural numbers, 1, 2, 3, 4, 5, etc. From this table plot another curve on the same sheet of paper which you employed in (*c*).

TO REPRESENT GRAPHICALLY THE MANNER IN WHICH ONE QUANTITY VARIES WITH ANOTHER

It is nearly always true that if we change one property of a body, some other property of the body will change at the same time. For example, the engineer of a running train increases the pressure of steam in the cylinders; as a result, the speed of the train increases. An iron rod is held in a gas flame; as we increase the temperature, we find that the length of the rod

increases also. If the amount of load on a canal-boat is increased, the depth of the keel below the water-line also increases.

When a change in one quantity is accompanied by a change in some other quantity, as in the examples just given, one of these quantities is said to **vary** with the other. Thus, the length of a rod varies with its temperature.

The manner in which one quantity varies with another may be conveniently represented on squared paper, by a method which will now be explained. The numbers given in the accompanying table were obtained as follows. A glass vessel resembling a flower-pot in shape, *i.e.* much wider at the top than at the bottom, was filled to different depths with water. This was done by pouring in, one after another, equal volumes of water, using a small test-tube as a measure. After the first measure was poured in, the depth of water in the vessel was found to be 2.9 cm., as recorded in the second column of the table. A second measure of water was then poured in, and the depth found to be 4.8 cm., as shown in the table. This process was continued until the vessel was full. Evidently, the depth of the water varies with the number of measures added.

Number of measures added	Depth of water
	cm.
0	0
1	2.9
2	4.8
3	6.3
4	7.6
5	8.7
6	9.7
7	10.6
8	11.4
9	12.2

On a sheet of squared paper, Fig. 12, the line along the bottom was chosen as the axis of X (see Crew's *Elements of Physics*, Art. 2), and the line along the left-hand side as the axis of Y. The origin is the point where these axes intersect, at the lower left-hand corner.

Starting from the origin, a scale of numbers was then laid off along the axis of X, to represent the number of measures of water added. Each space of five small divisions thus represents 1 measure. In the same way, distances along the axis of Y were laid off to represent the depth of water in the vessel, each space of five divisions here representing 1 cm. of depth.

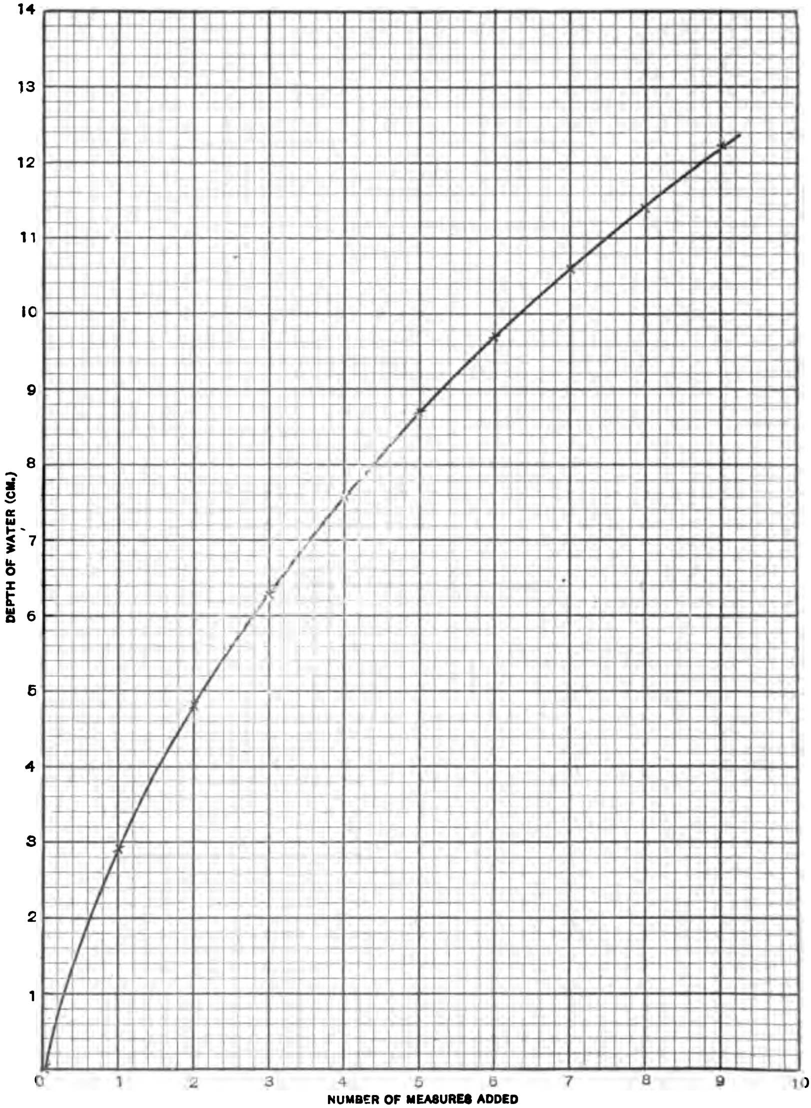

Fig. 12. — Curve illustrating the variation of one quantity with another.

We now propose to represent the state of things in the vessel at any instant by a point on the diagram. At the beginning, when no water has been added, the abscissa is zero; and since the depth is then zero, the ordinate is also zero. Hence, the point to be plotted is at the origin, as has been indicated by placing a small cross at that point.

Passing to the *second* line of the table (p. 19), we see that the number of measures of water added and the corresponding depth will be represented by a point whose abscissa is 1, and whose ordinate is 2.9. To find this point we go from the origin to the right, along the axis of X, a distance 1; then upward parallel to the axis of Y, a distance 2.9. The point reached is indicated by a cross as before.

In the same way, a new point is plotted for each pair of observations recorded in the table, each point representing by its abscissa the number of measures of water added, and by its ordinate, the *corresponding* depth.

Finally a *curve* is drawn, passing through all the points so obtained. (See Fig. 12.) This curve represents to the eye the manner in which the depth varies with the quantity of water poured in. In the lower part of the vessel, which is narrow, the addition of one measure of water increases the depth much more rapidly than at the top, where the vessel is wider. Hence, that part of the curve which corresponds to the bottom of the vessel is much steeper than the part which represents the upper portion. As the vessel fills up, the depth increases more and more slowly, and therefore the ordinates, which represent the depth, increase more and more slowly. Hence the curve as it leaves the origin becomes less and less steep.

Number of measures added	Depth of water
	cm.
0	0
1	2.0
2	3.9
3	5.9
4	7.8
5	9.8
6	11.7
7	13.7
8	15.6
9	17.5
10	19.5

We next proceeded to fill a glass vessel of uniform diameter

from bottom to top. (The shape of this vessel might be illustrated by a fountain pen, or a piece of glass tubing with the lower end stopped with a cork.) The preceding table shows

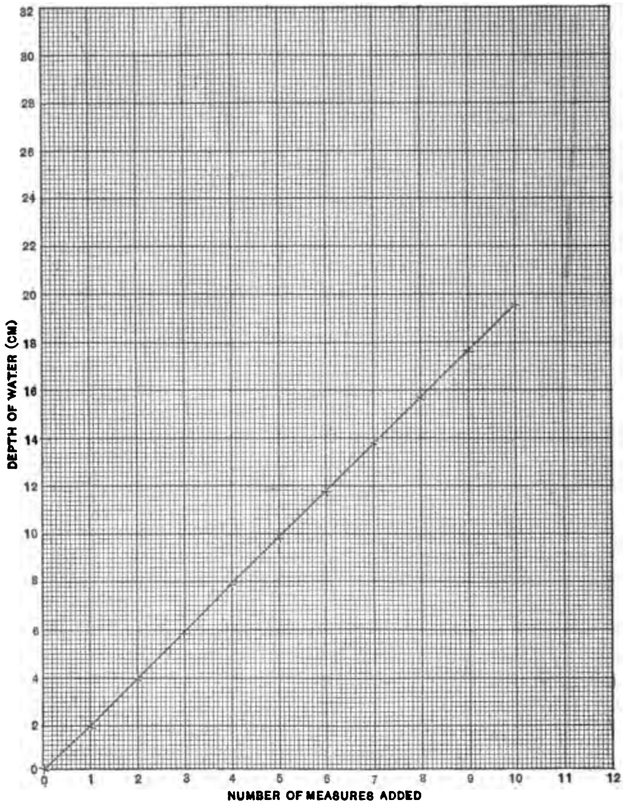

FIG. 13. — A straight line illustrating direct proportionality.

the depth recorded after each addition of one measure of water.

Evidently, in a vessel of this kind, the addition of a measure of water will increase the depth as much in one part of the

vessel as in another. Thus, the ordinates will increase with equal rapidity in all parts of the curve. This is the same as saying that the curve is equally steep at every point. In other words, it is a *straight line.* An examination of the curve plotted from the table will show that this is the case.

It is important to notice that in the example just mentioned, viz. in the use of a vessel of uniform diameter, if we double the amount of water contained in it, we shall double the depth; if the amount of water be increased five times, the depth will be increased five times. This is briefly expressed by saying that the depth **is proportional to** the quantity of water, or that the depth **varies directly as** the quantity of water. We see from the above, that **when one quantity is proportional to another, the curve representing the variation of these quantities is a straight line.**

And conversely, if on plotting a curve to show how one quantity varies with another, the curve turns out to be a straight line passing through the origin, we may then assert that the quantities are proportional to each other.

Exercise 10. — Curve Plotting

Apparatus. — Squared paper; sharp pencil.

Problem. — To plot a curve for the purpose of showing how one quantity varies with another.

Experiment. — (*a*) In Crew's *Elements of Physics,* facing p. 1, is a table showing the number of inches in 1, 2, 3, etc., centimetres. For example, 1 cm. = 0.3937 inch. Find, either from this table or by direct multiplication, the number of inches in every whole number of centimetres from 0 to about 15 or 20. For the purpose of this exercise, you will need only two places of decimals. Hence, you need record these values only to the *nearest* hundredth of an inch. Thus we find that 2 cm. = 0.7874 inch, which *to the nearest hundredth* may be written 0.79 inch. Enter these values in a two-column table, similar to the one on p. 21. These pairs of values may be plotted in a curve. But before you begin to

plot the points, lay off a scale of numbers along the axis of *X*, from 0 to 20, letting five small spaces represent 1 cm. Label this scale "Number of centimetres." Also lay off a scale on the axis of *Y*, letting ten small spaces represent 1 inch. Label this scale "Number of inches."

From the pairs of values in your table, now plot a curve on this sheet of paper, taking the number of centimetres as abscissas, and the number of inches as ordinates.

What is the form of the curve which you obtain? Is the number of inches in a length proportional to the number of centimetres in that length?

(*b*) A different form of curve may be obtained as follows: Enter in the first column of a table the natural numbers 0, 1, 2, 3, etc., up to 15. In another column enter the *squares* of these numbers.

Taking the natural numbers as abscissas, and their squares as ordinates, plot a curve. On the scale of abscissas let five small divisions represent unity; on the scale of ordinates let one small division represent unity.

In numbering scales of abscissas and ordinates *use only whole numbers, i.e.* do not insert fractional values. A reference to Figs. 12 and 13 will make clear the proper method of numbering the scales. These numbers should always be *at regular intervals, i.e.* 0, 1, 2, etc., or 0, 2, 4, 6, etc., or 0, 5, 10, 15, etc. Frequently it is more convenient to begin with some number which is not 0. Thus, if a series of quantities to be plotted as ordinates or abscissas all lie between 15 and 25, the scale may begin at 15 and end at 25.

(*c*) A curve may often be employed to find values of the ordinate or abscissa *which have not been observed.* For example, in the curve of Fig. 12 suppose we desire to know what the depth of water in the vessel would be after pouring in $2\frac{1}{2}$ measures of water. Finding 2.5 on the scale of abscissas, we observe the corresponding ordinate to be 5.6 cm., which is the desired depth. And, in general, any ordinate may be found from the curve when its abscissa is given.

From the curve plotted in (*b*) find approximately the squares of the following numbers: 1.5; 3.8; 11.2. Enter these in your report, and verify them by actual multiplication.

Exercise 11. — Measurement of an Irregular Area

References. — CREW, 12; HALL AND BERGEN, 14–15.

Apparatus. — Squared paper; cardboard of fairly uniform surface-density; shears; balance.

Problem. — To measure the area of a surface whose outline is irregular and whose area is, therefore, not easily computed.

Experiment. — (*a*) Ask your instructor to draw on a sheet of squared paper an irregular figure similar in shape to that shown in Fig. 14.

(*b*) Count the total number of *large* squares which are entirely included inside the figure. Draw a light pencil line over the boundary of these squares.

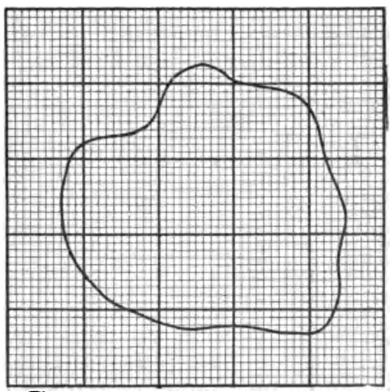

FIG. 14. — Illustrating the measurement of an irregular area.

Having recorded this number, proceed to count the total number of *small* squares which are entirely included within the figure and *not* included in the large squares already counted. How many of these small squares make one large square? What then will be the area of all these small squares in terms of one large square? Having recorded this number, proceed to count the number of small squares which are cut by the boundary of the curve in such a way that more than one-half the small square lies *inside* the boundary. Consider the parts of squares just counted as whole squares, and record the number in terms of one large square. Omit

those small squares of which more than one-half lies outside the boundary. By adding together the three numbers just recorded, you will obtain a fairly accurate value of the area of the surface enclosed by the boundary. In what unit is the area expressed?

(*c*) From a piece of uniform cardboard cut an irregular figure. Find its area as follows: On the same piece of cardboard lay out a regular figure, say a rectangle whose sides are 6 cm. and 8 cm. respectively. Cut the regular figure very carefully with a sharp pair of shears. Weigh each of these pieces of cardboard. Knowing their masses, and knowing the area of one piece of cardboard, proceed to compute the area of the other.

This method of measuring areas was employed in very early times by the Greeks.

Exercise 12. — A Study of Mass and Density

References. — CREW, 46–49; AVERY, 7, 155; CARHART AND CHUTE, 169; HALL AND BERGEN, 22–27.

Apparatus. — A circular cylinder, preferably of brass, aluminium, or glass, so that it will sink in water, but will not absorb water. Ends of cylinder should be turned off true. Simple pair of beam balances, sensitive, say to $\frac{1}{10}$ g. A small graduated jar, large enough to easily hold the cylinder.

Problem. — To get a clear idea of mass and density; and to learn one method for measuring each of these quantities.

Experiment. — (*a*) With a pair of vernier calipers, measure the diameter and height of the cylinder. Call the diameter d, and the height h. Measure each of these quantities at least three times.

(*b*) Compute the volume of this cylinder from the measurements which you have just made. Denote the volume of this cylinder by V, and show that

$$V = \frac{\pi d^2 \cdot h}{4} = \pi r^2 \cdot h = \text{area of base} \times \text{height},$$

where r is the radius of the base. Is your answer in cubic centimetres or in cubic inches?

(c) Now weigh the cylinder on a pair of balances. This process will give you the amount of matter in the cylinder. For if it weighs 60 grammes, this means simply that the cylinder has 60 times as much matter in it as there is in a one-

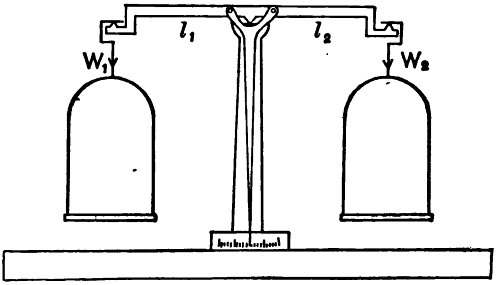

FIG. 15.

gramme piece. Or, if it weighs 17.5 grammes, then it has 17.5 times as much matter in it as there is in a one-gramme piece. If it weighs x grammes, it has x times as much matter in it as there is in a one-gramme weight.

(d) The next problem is to find how much matter there is in one unit of volume, say 1 cubic centimetre, of this cylinder.

You know already how much matter there is in the entire body, for you have weighed it. You know also the cubic contents, or volume, of the body. From these data compute the amount of matter in 1 cubic centimetre of the body. For this purpose you may assume that the body is uniform throughout.

Definition of Mass

We might use the phrase "amount of matter" in speaking of all the various bodies which we shall study during the remainder of the year; but it has been found more convenient to use the word **mass**, which is shorter, and means exactly the same thing as *amount of matter*.

Definition of Density

We might also use the expression "amount of matter in unit volume" throughout the remainder of this book; but students of science have found it more convenient to use the word **density** to denote the *amount of matter in a unit of volume.* Accordingly, in August, 1900, the International Congress of Physicists at Paris agreed to use the word density to mean only "the ratio of mass to volume."

(*e*) Another convenient method of measuring the volume of a body is as follows: By means of a thread, lower the cylinder into a jar graduated in cubic centimetres, and partly filled with water. The amount by which the water rises in the graduated vessel will be equal to the volume of the body immersed. Obtain the volume of the cylinder in this way, and compare it with the value which you computed above.

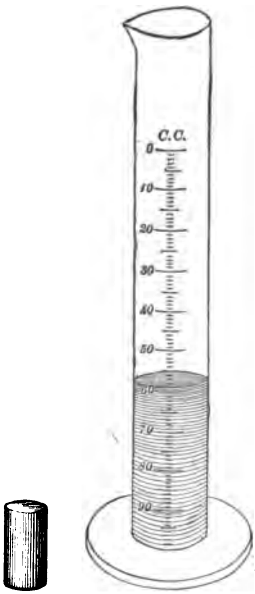

Fig. 16.

(*f*) Of these two methods, which do you consider the more accurate? State the reasons upon which you base your opinion.

Exercise 13. — Another Determination of Density — Case of Solids

References. — Gage, 6; Rowland and Ames, 14; Carhart and Chute, 169; Crew, 49.

Apparatus. — Two or three solids of some material other than that employed in Exercise 12, say glass, aluminium, and hard rubber. Perhaps the most convenient shape for these bodies is that of a circular cylinder. A parallelopiped may be used if

preferred; also an irregular figure when only the method of immersion is used for obtaining the volume. The remainder of the apparatus is the same as that used in Exercise 12.

Problem. — To obtain further practice in the measurement of the fundamental quantities, mass and volume.

Experiment. — (*a*) Proceed as in Exercise 12 to find the volume, that is, the cubic contents, of each of these bodies. Then find the total amount of matter, that is, the mass of each body. What instrument do you use for measuring mass?

(*b*) Next compute the ratio of the mass to the volume. Is the ratio of mass to volume the same as the amount of matter in unit volume?

Arrange your results in a table, as follows:

Substance	Height of cylinder (h)	Diameter of cylinder (d)	Mass of cylinder	Volume of cylinder $\left(\frac{\pi d^2 \cdot h}{4}\right)$	Density by first method	Volume by immersion	Density by second method
Glass							
Aluminium							
Hard Rubber							

What is the difference between a "body" and a "substance"? Is density a property of a body, or of the substance of which the body is made?

Exercise 14. — Another Determination of Density — Case of Liquids

References. — Crew, 49; Avery, 155.

Apparatus. — Balance; 50 cc. alcohol; 50 cc. distilled water; saturated solution of copper sulphate; small beaker; fine shot; graduated glass vessel, preferably a burette holding 50 cc.

Problem. — To measure a definite volume of liquid, to weigh it, and then to compute its density by use of the defining equation,

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}.$$

Experiment. — (*a*) Having cleaned and carefully dried your beaker, place it on one pan of the balance and counterpoise it by placing fine shot on the other pan of the balance.

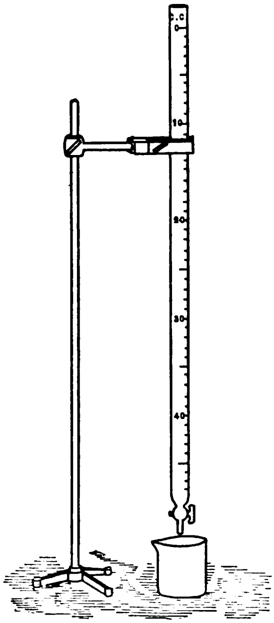

FIG. 17. — Burette.

(*b*) Next partly fill the burette with one of the liquids whose density you wish to measure. Read and record the volume of liquid in the burette.

(*c*) Now let about 30 or 40 cc. of liquid run from the burette into the beaker. Again read and record the volume of liquid in the burette. The difference between this reading and the former one will give you the volume of the liquid in the beaker.

(*d*) Replace the beaker on its scale pan, and weigh it with the liquid in it. Add weights to the fine shot until you just balance the beaker and the liquid. The mass of the weights added will be the mass of the liquid. Record your results in a table as follows, and repeat the process for two other liquids:

Name of liquid	First reading of burette	Second reading of burette	Volume of liquid	Mass of liquid	Density of liquid
Alcohol					
Copper Sulphate					
Water					

Which error do you consider the larger, that which you make in measuring the volume or that which you make in measuring the mass?

State the reasons for your opinion.

Exercise 15. — The Slide Rule

Apparatus. — Slide rule. This instrument is a simple machine for multiplying and dividing. As shown in Fig. 18, it consists of three parts, a fixed scale, a movable scale, and a sliding index. The scales on the fixed and movable parts are graduated from 1 to 100, and are as nearly as possible alike, being in fact a single scale divided lengthwise into two portions, as indicated in Fig. 19. One scale may thus be made to slide along the other. The sliding index is used merely to record any desired reading on the fixed scale.

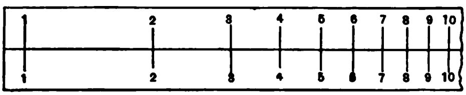

Fig. 19. — Illustrating how the scale of the slide rule is made.

(A second scale, graduated from 1 to 10 is placed on most slide rules, but this will not be needed in the present exercise.)

Problem. — To learn how to multiply and divide with the slide rule.

Experiment. — (*a*) Bring mark "1" of the movable scale opposite to mark "2" of the fixed scale. See Fig. 20. You will then find that 4 on the fixed scale lies opposite to 2 on the movable scale; in like manner 6 is opposite 3, 100 opposite 50, etc. In general, every number on the fixed scale is twice the corresponding number on the movable scale.

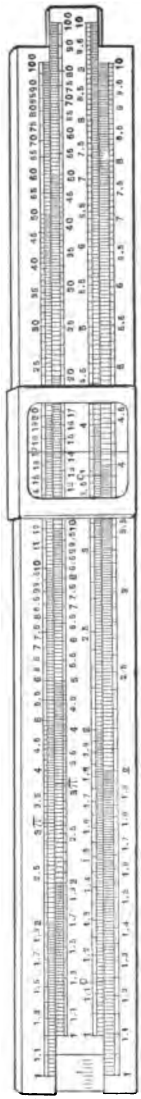

Fig. 18. — The slide rule.

Now make 1 on the movable scale coincide with 3 on the fixed scale, and it is seen that

$$\left\{\begin{matrix}\text{Any number}\\ \text{on fixed scale}\end{matrix}\right\} : \left\{\begin{matrix}\text{corresponding number}\\ \text{on movable scale}\end{matrix}\right\} :: 3 : 1.$$

Hence, to obtain the product of two numbers, find one of the numbers on the fixed scale, and bring 1 of the movable scale opposite to it. Find the multiplier on the movable scale. The desired product will be found on the fixed scale opposite the multiplier.

For example, multiply 17 by 3. Find 17 on the fixed scale. Bring mark 1 of the movable scale to this point. Opposite 3 on the movable scale is 51, the product.

(*b*) To obtain the continued product of $3 \times 5 \times 2$, proceed thus: Find 3 on the fixed scale. Opposite to it place 1 on the movable scale. Bring the sliding index to 5 on the movable scale, thus indicating the product of 3 and 5. It is, however, *unnecessary to read this product*, because it is a partial product, and is recorded by the index. Now bring mark 1 of the movable scale to the index. Opposite 2 on this scale will be found the final product, 30.

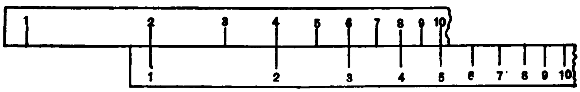

FIG. 20. — Illustrating the use of the slide rule.

(*c*) **To divide one number by another we have simply to reverse the process used in multiplying.** For example, divide 63 by 7. Find 63 on the fixed scale, and bring 7 on the movable scale opposite to it. The quotient, 9, will now be found on the fixed scale opposite 1 on the movable scale. For, as already explained, 63 : 7 : : 9 : 1.

(*d*) Solve the following problems with the slide rule, and verify the results by ordinary arithmetic. Notice that the value of a division varies in different parts of the scale, so that

care is needed to read the scale correctly. A common error in the use of the slide rule is to misread the position of the index.

(1) 7×9.
(2) 2.5×14.
(3) 25.5×2.35.
(4) $2 \times 3 \times 11$.

(*e*) Should the product be greater than 100, it may be found by bringing the *100-mark* of the movable scale opposite the required number on the fixed scale. The product *divided by 100* will then be found opposite the multiplier.

(5) 45×8.
(6) $\frac{21}{7}$.
(7) $\frac{30.5}{4.65}$.
(8) $\frac{55.5}{5.55}$.

(*f*) Solve $\frac{14 \times 9}{5}$. We might begin by multiplying 14 by 9, but since their product is greater than 100, it is more convenient to divide first. The process will then be as follows: Find 14 on the fixed scale. Opposite to it place 5 on the movable scale. Opposite 9 on the movable scale is found 25.2, the required solution. In the following examples use the rule in such a way as to obtain the final result *without reading off any partial results.*

(9) $\frac{30.6 \times 2.5}{32.9}$.
(10) $\frac{71 \times 10.3}{30.1 \times 5.9}$.

(11) Find the area of a circle whose radius is 5 inches, using the formula, area $= \pi r^2$.

This simple instrument will save you so much time that it is well worth your while to master it thoroughly. When you have pursued mathematics farther, you will find that this instrument sheds much light on the subject of logarithms.

In your report illustrate the use of the slide rule by explaining how you worked one or two of the above examples.

Exercise 16. — To etch a Scale of Millimetres on Glass

Apparatus. — Smooth board of soft wood, about 2 feet long; millimetre scale of any length, but preferably of steel; a beam compass, made of a rod of hard wood 12 or 15 inches long; near each end of the rod a large needle is driven through at right angles to its length, the points projecting about half an inch; strip of glass — a microscope slide is good; half-dozen small thumb tacks, such as are used by draughtsmen; paraffin wax; Bunsen burner; solution of hydrofluoric acid.

Experiment. — (*a*) Place a small piece of paraffin on the strip of glass. Hold the strip horizontally at a height of several

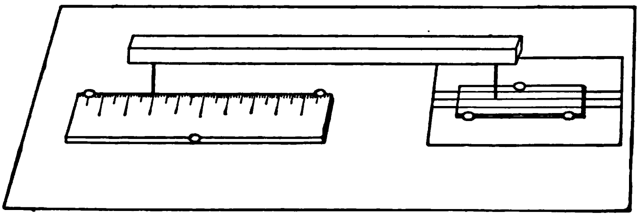

FIG. 21. — Illustrating manufacture of a millimetre scale.

inches above a Bunsen flame until the wax melts and spreads evenly over the surface. While warm stand the strip on end, allowing the surplus wax to drain off on a piece of paper. When cool, the strip will be coated on one side with a thin uniform layer of paraffin.

(*b*) Take a slip of paper a little larger than the glass. Draw a straight line lengthwise along the middle of the paper. Parallel to this line draw two others, one 5 mm. above it, the other 5 mm. below it.

Lay the ruled paper on the board, near the right-hand end, with the lines roughly parallel to the sides of the board. On the paper lay the strip of glass, with its coated side uppermost. The edges of the glass should be parallel to the pencil lines, and about equally distant from the middle one. Secure

the glass in this position with three thumb tacks, as shown in Fig. 21. With more tacks fasten the millimetre scale to the board with its graduated edge about in line with the lowest of the three lines on the paper slip.

(*c*) Place one needle point of the beam compass on a centimetre mark of the scale. Using this as a centre, scratch with the other needle a mark through the wax coating on the glass. This mark should begin at the top line on the paper slip, and end at the bottom line. Now place the left-hand needle on the next millimetre mark of the scale, this time making the scratch in the paraffin extend from the middle pencil line to the bottom one.

In this way rule a scale five or more centimetres long. Make the even centimetre marks extend from the top to the bottom line on the paper, and the intervening millimetre marks half as long, except the half-centimetre marks, which should extend a little above the middle pencil line.

Cautions. — To obtain a neat and accurate scale, the following precautions must be observed: (1) Use very light pressure on the beam compass; otherwise the needle will bend a little, thus spacing your marks unevenly. Hold the left-hand end in position by placing a finger-tip on the beam, over the needle, the arm resting on the table. Grasp the right-hand end lightly; the weight of the beam itself is probably sufficient to scratch through the wax and lay bare the glass. (2) Make each mark with a *single* stroke. If you draw the needle twice over the same line, you will destroy its sharpness.

(*d*) Remove the glass strip from the board. Engrave your name in one corner with a needle mounted in a wooden handle. Any stray scratches may be erased by touching with a heated wire.

(*e*) Now ask the instructor to put the hydrofluoric acid on the scale for you. This may be done after laboratory hours. The effect of the acid will be to etch the scale permanently upon the glass strip. The acid is best applied with a flat strip of wood. Lay the glass on the edge of the table. Breathe on

it to moisten the surface. Dip one end of the stick into the acid bottle, and draw its flat side very lightly over the wax film once or twice. Let the acid act for one or two minutes, rinse it off, dry the glass strip with a towel. Warm it over a flame, and remove the melted paraffin with pieces of newspaper.

NOTE ON THE DIFFICULTY OF ILLUSTRATING THE LAWS OF MOTION IN THE LABORATORY

Owing to the fact that friction prevents us from controlling velocities and accelerations in the laboratory, we have naturally omitted the description of experiments dealing with this part of the subject.

A series of simple exercises illustrating the laws of uniform and accelerated motion in a quantitative way is greatly to be desired. These laws have been thoroughly established by astronomical phenomena from which friction is practically absent. The need of such experiments in the laboratory is perhaps lessened by the fact that the behavior of a body moving according to the simpler laws of motion can be so easily computed. See the chapter on *Mechanics* in any good textbook of physics.

CHAPTER II

GENERAL PROPERTIES OF MATTER

SECTION 1.—THE INERTIA OF MATTER

The amount of matter in a body is a quantity which we have very frequently to measure, not only in laboratory practice, but also in everyday life. Other things being the same, the price of a package of coffee depends upon the amount of coffee in it, *i.e.* upon the mass of the coffee. If the mass of the coffee is doubled, your grocer charges you twice as much for it; if the mass is halved, he charges you half as much for it. Indeed, most kinds of food are sold by mass, and for each article the cost is proportional to the mass.

The grocer measures the mass of a body by use of a pair of scales, which is an instrument having two equal arms with a pan attached to each arm. Into one of these pans is placed the body to be "weighed," and into the other pan are placed some known masses. These known masses are added until the pull of the earth on them is just equal to the pull of the earth on the article in the other pan. The mass of the body is then said to be the same as the known mass of the "weights." *But really all that the grocer has determined is that the pull of the earth on the package of coffee is the same as the pull of the earth on the "weights" in the other pan.*

THE INERTIA BALANCE

But the mass of a body may be measured by another method, which does not depend at all upon the fact that the earth

attracts bodies; but rests simply upon the fact that the inertia of a body is proportional to its mass. This tendency of a body to remain in its present condition, whether of rest or of motion, is measured by its mass. In short, **mass is the measure of inertia.** If a package of sugar "weighs" 3 kilogrammes, then its inertia is said to be "3"; if its mass is 25 kilogrammes, then its inertia is 25, and so on.

When each of two masses, m_1 and m_2, are acted upon by equal forces, say F, these masses receive accelerations. If we denote these accelerations by a_1 and a_2 respectively, we may describe the effect of the force on each of these bodies by

writing $$F = m_1 a_1 \text{ for the first mass.}$$

and $$F = m_2 a_2 \text{ for the second mass.}$$

Hence $$\frac{m_1}{m_2} = \frac{a_2}{a_1}.$$

In other words, the accelerations are inversely proportional to the masses, when the force is constant. This is merely an accurate statement of the well-known fact that the velocity of a heavy body is not so easily changed as that of a light body. If, in any such case, the acceleration a_1 is the same as a_2, we know at once that the mass m_1 is equal to the mass m_2.

This general principle is employed in the following experiment for the purpose of telling when two masses are equal. We employ a spring to keep a scale pan in vibration. And this scale pan, when in any given position, is always acted upon by the same force, viz. the twisting force of the spring. Here we do not have to measure the accelerations a_1 and a_2, for we can more easily measure the period of vibration of the scale pan. The advanced student will learn that if, in any two cases, the scale pan has the same period of vibration, *the load in the scale pan* must be the same in each case. The step by which we pass from equality of periods to equality of accelerations is here omitted. *The important thing is that equality of periods means equality of masses.*

Exercise 17. — The Inertia Balance

References. — CREW, 45, 51; ROWLAND AND AMES, 8; HALL AND BERGEN, 245–246; WENTWORTH AND HILL, 174–176; AVERY, 26–27; GAGE, 25.

Apparatus. — Some kind of inertia balance, such as that of Hicks or such as that described below; a watch, a seconds-clock, or preferably a stop-watch; set of "weights"; a body to be weighed.

Problem. — To measure the mass of a body without measuring its weight.

Experiment. — A simple and convenient inertia balance is that illustrated in Fig. 22.

The rigid arm, A, carries a cone-shaped scale pan. If the arm A is rotated about the steel wire SS' as an axis, this wire is twisted. If now the arm A is released, it will vibrate to and fro through its position of equilibrium with a definite and measurable period.

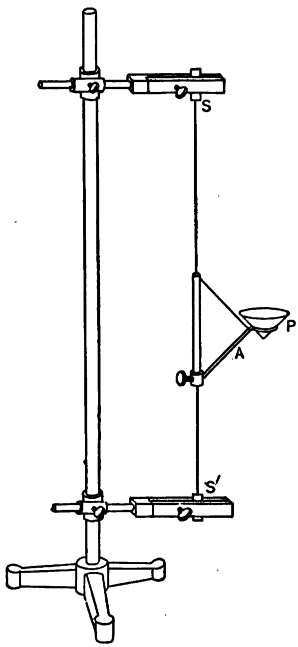

FIG. 22. — A balance which measures the mass of a body without measuring its weight.

What is meant by the "period" of a vibration? (See Crew's *Elements of Physics*, Art. 40.)

(a) Place the body whose mass is desired in the pan, P, of the balance, with its centre of mass as nearly as possible over the apex of the cone. Set the arm in vibration about its vertical axis, and measure, with a watch, or clock, the time of 10 or 20 complete vibrations.

Perhaps the simplest way is the following: Press the pan to one side and let it go so that it passes through its position

of rest on the even second, say when the second hand is at "0," "10," or "20," etc. Then count the 20 succeeding passages of the arm in the *same* direction, noting the instant at which the 20th vibration is completed. Repeat this with the utmost care five times. A little practice is needed before you can do this well.

(*b*) Now replace the body in the pan with a mass taken from a set of "weights," choosing one which you think has about the same mass as the body which you have just timed. Again take the time of 20 vibrations. Suppose the known mass vibrates more slowly than the unknown mass, which of the two is the greater?

(*c*) Perhaps the "weight" which you have selected is greater than the unknown mass; in this event, take another "weight" which is a little less than the unknown mass. Place this weight in the pan and measure the time of 20 vibrations.

Having found, in this way, one mass which is a little greater, and one which is a little less than that of the unknown body, we can "guess" intelligently as to the unknown mass.

The following determination of an unknown mass was made with an inertia balance similar to that shown in Fig. 22.

Period of Vibration with	First trial	Second trial	Third trial
	sec.	sec.	sec.
Unknown mass in pan	1.09	1.08	1.08
50 g. in pan	1.01	1.00	1.01
70 g. in pan	1.14	1.16	1.14

$\therefore$ Required mass of body = 62.3 g., 60.0 g., 60.7 g.

Mean value of unknown mass = 61.0 g.
Value as determined on ordinary balance = 60.758 g.

Observer, R. A. PORTER, July 1, 1901.

Exercise 18. — The Addition of Forces

References. — Crew, 5, 57; Rowland and Ames, 36; Avery, 70; Carhart and Chute, 54–56; Hall and Bergen, 66.

Apparatus. — Three spring-balances capable of weighing up to 3 or 4 pounds; a protractor; a sheet of white drawing paper; three small iron clamps; millimetre scale; 2 yards of fish-line.

Problem. — Having given two forces, applied at any point, to find a third force which will produce exactly the same effect upon the point as these two. A study of vector quantities.

Experiment. — (*a*) Fasten a sheet of white paper on the table by driving pins at the corners. Fasten the balances, *A*, *B*, and

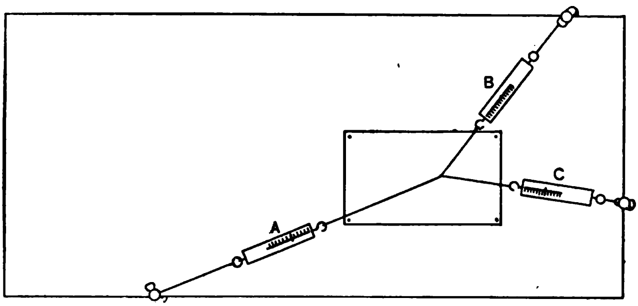

Fig. 23. — Illustrating the addition of vectors.

C, on the table in a position somewhat similar to that shown in Fig. 23. The simplest manner of doing this is, perhaps, by use of small iron clamps which are attached, screw uppermost, to the edge of the table. To each spring-balance is attached a piece of cord, say half a metre in length. These three cords are all tied together at one end, or else are all tied to a small ring not more than $\frac{1}{2}$ cm. in diameter. The other ends of the threads are each attached to the hooks of the spring-balances.

You can now adjust the clamps so that each balance will exert a considerable force upon its cord. The ring, or knot where the cords meet, is a small particle upon which three different forces act at the same time. The cords show the

directions of the forces; the balances indicate the magnitudes of the forces. The fact that the particle at the centre is not accelerated shows that the three forces are in equilibrium; or in other words, it shows that their sum is zero. We now propose to compute the resultant of two of these forces, and then to compare this resultant with the third force.

(*b*) With a sharp lead pencil make two distinct dots exactly under each of the three cords, one dot near the knot, the other as far away from the knot as possible. The lines joining these pairs of dots will give the directions of the forces.

(*c*) It remains only to find the magnitudes of the forces. This is easily done by reading the scales of the three spring-balances. Having made these readings, record each one alongside the line which you have drawn to represent that force. In case your spring-balances do not read "0" when there is no load on them, how will you correct this error?

These three lines, if carefully drawn, will meet very nearly in a point underneath the knot. Starting from this point, measure off, along each of the three lines, **a length which is numerically equal to the force in that direction.** Put an arrow on each line showing which way the force acts. The three lines so drawn are three vectors, each line completely representing one force.

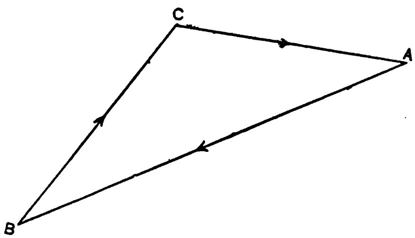

FIG. 24.—Equilibrium of three forces.

(*d*) Choose any two of these vectors, and proceed to find their resultant by completing the parallelogram. Put an arrow on this resultant to show which way it acts. How does this resultant compare in magnitude and in direction with the third force? Enter this diagram in your report. It is most easily copied by laying it over a page in your note-book and pricking through the necessary points with a pin.

(e) Repeat this experiment for a case in which two of the forces make an angle of about 90°. Repeat it also for a case in which two of the forces make an angle of about 30°.

Suppose these forces are such that when plotted end to end, as in Fig. 24, they form a closed triangle, will they be in equilibrium? Is this true, regardless of which way the arrows point?

Exercise 19. — Further Study of Force and Inertia

References. — Crew, Chap. II., also Arts. 45, 108; Rowland and Ames, 60.

Apparatus. — A small spiral spring made of brass wire which is a little more than a millimetre in diameter. The spiral should have a diameter of from $1\frac{1}{2}$ to 2 cm. The length of the spiral when closely coiled may well be about 10 cm. A rigid upright to support this spring; scale pan; set of "weights" running from 5 to 200 g.; clock or stop-watch.

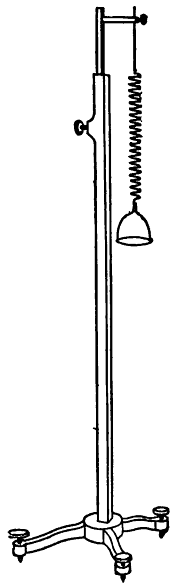

Fig. 25. — Variation of period of vibration with load.

Problem. — To find how the period of a vibrating spring varies as we change the load which the spring carries. A study of the inertia which bodies offer to forces of translation.

Experiment. — (a) Having arranged your spring as indicated in Fig. 25, begin by placing a load of 200 g. in the pan. Seat yourself so that you are able to see both clock and spring at the same time, and measure the time occupied by the spring in making 30 complete vibrations. Record your results in the form of a table, writing down both the load in the pan and the time of thirty vibrations.

(b) Now change the load in the pan to 190 g.; and so on, decreasing the load each time by 10 g. Measure the duration of 30

vibrations corresponding to each load, and record this in the table mentioned above.

With any given load in the pan, does the period of vibration change when the amplitude of vibration is changed?

If you remove a "weight" from the pan and suspend it, by a light string, at a distance of, say, 6 or 8 inches below the pan, is the period of vibration altered?

(*c*) Plot your results in the form of a curve, using *masses as abscissas* and the corresponding *periods of vibration as ordinates.*

N.B. The mass of the scale pan is always to be counted as a part of the load. Ought any consideration to be given to the mass of the spring?

(*d*) Take several of your observations and divide the period T by the square root of the load $\sqrt{m}$. If your spring is fairly light, and if your observations have been well made, you will be surprised to find how nearly uniform are the values of $T/\sqrt{m}$. What inference may you draw from the fact that $T/\sqrt{m}$ is a constant? Or, more directly, how does T vary with m?

It is important to note, that, whatever the mass in the pan may be, the force acting upon it is always the same, whenever the displacement of the spring is the same. Hence, as the mass in the pan is increased, the acceleration is diminished, and the period increased.

Exercise 20. — Moments of Force

References. — Crew, 60–62, 74, 100; Rowland and Ames, 37; Wentworth and Hill, 49–52; Gage, 47–48; Avery, 130–131; Hall and Bergen, 224–225.

Apparatus. — Lever, made of a wooden metre stick, balanced about its middle point; use a stout sewing needle for the axis of suspension; bore a hole slightly larger than the needle through the 50-cm. mark of the metre stick, at a point about 5 mm. from one edge; a support for the lever, as shown in

Fig. 26; two scale pans, such as shown in Fig. 27, with hooks for hanging them upon the lever; set of weights; "index bar" of wood, with the ends sawed off square, and of such a length as to stand with the top surface at an even height with the

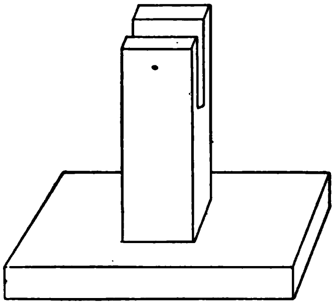

FIG. 26.

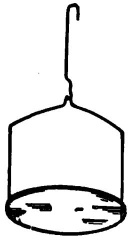

FIG. 27.

upper edge of the lever, when the latter is horizontal; short piece of copper wire, about No. 16.

Problem. — To verify the law of equal moments, namely, that when a body, free to rotate about an axis, is in equilibrium, the total moment of force acting upon it is zero.

Experiment. — (*a*) Suspend the metre stick by an axis through its 50-cm. mark; and, leaving off the scale pans, bring the stick into equilibrium in a horizontal position, as shown in Fig. 28.

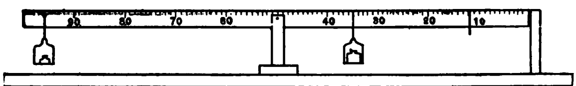

FIG. 28. — Illustrating the earliest known law of mechanics.

This can be done by hanging on the lighter arm a piece of copper wire, bent into the form of a U. Make the U narrow, in order that it may cling to the lever; when once adjusted, it is not then likely to be accidentally moved. Stand the "index bar" on the table, close to and just beyond the lever. This will show when the lever is horizontal.

(*b*) Weigh each of the scale pans on a balance, determining their masses to the nearest centigramme, and record them in your notes.

(*c*) Add a mass of, say 20 g. to the pan on the left arm of the lever, and place the pan at a distance of, say 40 cm. from the axis. Add a different mass, say 50 g., to the pan on the right, and move the pan along the lever until you obtain equilibrium.

(*d*) Compute the *moment of force* acting upon the left arm. The *force* acting on this arm is the weight of the mass upon the left pan, added to the weight of the pan itself. The *moment of force* is the product of this force by its distance from the axis, measured horizontally along the lever. Compute also the moment of force acting on the right arm of the lever.

If M_1 is the mass of the left pan plus its load, and g the acceleration of gravity, the weight (or force) acting is M_1g, and the moment of force is M_1gl_1, where l_1 is the horizontal distance from the force to the axis. Similarly, the moment of force on the right arm may be written M_2gl_2, where M_2 is the mass on the right arm, and l_2 its horizontal distance from the axis. (Crew's *Elements of Physics*, Art. 100.) Do these two moments tend to rotate the lever in the same or in opposite directions? Should they have like or unlike signs? How do their numerical values compare with each other? What is the sum of two quantities which are numerically equal, but opposite in sign?

Note carefully that moments of force play the same rôle in producing rotation that linear (or ordinary) forces play in producing translation. In all your thinking distinguish clearly between *force* and *moment of force.*

(*e*) Change each of the masses used, and place them at different distances from the axis. Repeat (*b*), (*c*), and (*d*), bringing the lever into equilibrium in each case. Make at least five different tests of the equality of moments. Record all your results in tabular form.

A table such as the following may be employed:

Obs.	LEFT ARM: Mass of left pan = grammes				RIGHT ARM: Mass of right pan = grammes			
	Mass in pan	Total mass	Distance from axis	Moment	Mass in pan	Total mass	Distance from axis	Moment
	g.	g.	cm.		g.	g.	cm.	
1								
2								
etc.								

The principle of the lever which you have here studied was first distinctly enunciated by Archimedes, 287–212 B.C.

Exercise 21. — Rotational Inertia

Reference. — CREW, 52–55.

Apparatus. — A light steel tube about 1 foot long and $\frac{1}{4}$ inch in diameter; two lead or brass disks which slide or screw on this steel tube. These disks may well be about $\frac{1}{2}$ inch thick and 2 inches in diameter. A torsion wire supporting rod and disks as indicated in Fig. 29. The diameter of this wire should be such that the average period of vibration lies in the neighborhood of from 1 to 5 seconds. A seconds-clock, a watch, or, preferably, a stop-watch.

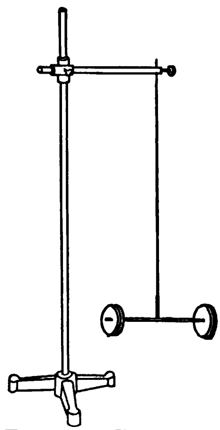

FIG. 29. — Illustrating the resistance which bodies offer to being set in rotation.

Problem. — To study the inertia which a body exhibits when a moment of force sets this body in rotation; and especially to note the difference between the inertia which bodies offer to being set in translation and that which they offer to being set in rotation.

Experiment. — (*a*) Slide or screw the disks as near as possible to the centre of the horizontal bar. Note that the system, that is the rod and its load, comes to rest in a perfectly definite position; and vibrates through equal angles on each side of this position. What kind of motion is this called? See Crew's *Elements of Physics*, Art. 36.

In fact this bar and its two disks form a horizontal pendulum, vibrating about a vertical axis. This piece of apparatus is sometimes called a torsion pendulum.

Proceed to measure the time required for, say, twenty complete vibrations of this pendulum. If you use a clock for this purpose, sit where you can see both the clock and the pendulum at the same time. N.B. *Be careful in counting the number of vibrations not to count "one" at the beginning of the first vibration. Wait until the first vibration has been completed; then count "one"; at the end of the second complete vibration count "two," and so on.* Record both the time of twenty vibrations and the distance between the inner faces of the disks. Does the period of vibration depend upon the amplitude of vibration?

(*b*) Now move the disks apart until the distance between the two inner faces is about 2 cm. *greater* than during the previous experiment. Measure the distance between the inner faces. Again compute the period of vibration by measuring the time required for twenty, or perhaps ten, complete vibrations.

(*c*) Repeat these observations after removing each of the disks from the vertical axis, a centimetre at a time. The distance between the inner faces of the disks will thus increase 2 cm. at a time.

Record your observations as follows:

Obs.	Distance between inner faces of disks	Time required for —— vibrations	Period
	cm.	sec.	sec.
1			
2			
etc.			

Plot your results in a curve, using for abscissas the distances between the inner faces of the disks; and for ordinates, the periods of vibration.

As the disks are moved farther away from the centre of the rod, does the mass or weight of the body change? Is there any change in the moment of force with which the twisted wire tends to bring the pendulum back to its position of rest? Is there any change in the inertia which the pendulum offers to rotation? Why is most of the matter in a fly-wheel placed out near the rim of the wheel?

THE CHEMICAL BALANCE

The principle of moments which we have just been studying is that employed in the ordinary balance used by grocers. Butchers generally use a spring-balance which is based upon the fact that the elongation of the spring is proportional to the load. But all accurate weighing in the laboratory is done on balances which have arms very nearly equal. The position of the balance beam is observed when there is no load on either pan. This position of equilibrium is generally indicated by means of a long pointer which moves in front of a fixed scale. Then a load is placed in one pan, while in the other pan are placed weights just sufficient to bring the pointer back to its original position of equilibrium.

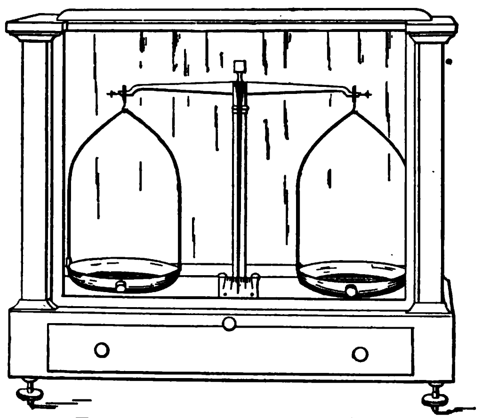

FIG. 30. — Simple chemical balance.

We then know, as proved in Exercise 20, that the moment of force exerted by the weights is equal and opposite to that exerted by the load.

Now each pan of a good balance is freely supported on a knife edge; and *the load in the pan, therefore, acts as if it were all concentrated at this knife edge.* Let us call the mass of the load M_1 and the mass of the weights M_2. Then if the distance between the central knife edge and that which supports the load be called l_1, and the distance between the central knife edge and that supporting the weights be called l_2, we may express the fact that the total moment of force is zero by writing

$$M_1 l_1 g + M_2 l_2 g = 0,$$

and since $$l_1 = -l_2, \text{ very approximately,}$$

$$M_1 g = M_2 g,$$

or $$M_1 = M_2, \text{ very approximately.}$$

Thus in the chemical balance, *we obtain two equal masses by first obtaining two equal moments of force.* For still more accurate weighing, one must not assume that the arms of a balance, even when well made, are exactly equal. To measure the ratio of the arms, l_1/l_2, by means of two independent weighings is a beautiful problem, adapted to the more advanced student.

Exercise 22. — Specific Gravity of a Liquid — Specific Gravity Bottle

References. — Carhart and Chute, 173; Wentworth and Hill, 75; Avery, 160; Gage, 116.

Apparatus. — Specific gravity bottle; or, if preferred, a small, narrow-necked flask, having a fine circular mark etched on the neck; balance and set of weights; solution of copper sulphate.

Problem. — To find the specific gravity of a solution of copper sulphate by the use of the specific gravity bottle.

Experiment. — (*a*) The specific gravity bottle is a small flask, provided with a perforated ground-glass stopper. The maker

of the bottle has carefully adjusted its volume, so that it will hold a given mass of pure water at some definite temperature. The mass of water which the bottle will hold is generally marked on its side. (See Fig. 31.)

By the balance determine the mass of the empty bottle with its stopper.

(*b*) If the number of grammes of water which the specific gravity bottle contains when full is marked upon the side of it, record this number in your note-book.

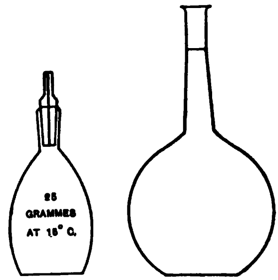

FIG. 31.—Two forms of specific gravity bottle.

If a common flask is made use of, it will be necessary for the student to determine this quantity for himself. Fill the flask with water up to the mark on its neck. Remove all air bubbles from the sides of the flask before the water quite reaches the mark. At the last, add the water slowly, a drop at a time, until the *lowest part* of the water surface has been brought opposite to the mark on the neck. If a trifle too much should be added by accident, the excess may be removed on the end of a glass rod, or lead pencil, or with a strip of blotting paper. Wipe off all water that may adhere to the outside of the flask, or to the inside of the neck above the water line. To do this use a narrow strip of blotting paper. Weigh the flask and water on the balance, and hence compute the mass of the water.

(*c*) Empty out the water, and fill the bottle with the solution whose specific gravity is desired. Use the same precaution in filling, as in (*b*). Weigh the bottle full of the solution, and compute the mass of the solution.

(*d*) You have now the mass of a certain volume of the solution and the mass of an equal volume of water. The ratio of the first of these masses to the second is called the **specific gravity** of the solution. Record all your data in a suitable table, and in the last column of this table place the value which you have computed for the specific gravity of the solution.

SECTION 2.—ILLUSTRATIONS OF ENERGY

Friction

When one body is made to slide upon another, there is always a force which holds back and opposes the motion. Thus, a sled set in motion on level ice and then left to itself, or a book suddenly pushed along a table, will sooner or later be brought to rest by the action of this retarding force. The name given to this force is **sliding friction**, or simply **friction.**

The amount of friction between two bodies depends on the material of which the two bodies are made, and on the degree of smoothness of the sliding surfaces. Thus, the friction between two iron blocks is not the same as that between two blocks of brass, and both of these differ from the friction between a block of iron and a block of brass.

The friction also depends on the force with which the two sliding surfaces are pressed against each other. Thus, as every one knows, if a street car is to be stopped slowly, the brakes are applied to the wheels lightly; but if a sudden stop must be made, they are applied with greater force, in order that the retarding force may be greater.

Suppose a spring-balance to be attached to a brick in order to measure the force required to drag the brick along the floor. Let the balance indicate, say 24 ounces, while the brick is moving uniformly. Then if a second brick be placed on top of the first, thus doubling the force with which the lower brick presses against the floor, it will be found that the balance will indicate 48 ounces. In other words, the amount of friction is very nearly proportional to the amount of force pressing the bodies together. The *ratio* of the force of friction to the force of pressure* is called the **coefficient of friction.** Thus, if the mass of either brick, in the example just cited, were 60 ounces, the coefficient would be $\frac{24}{60}$, or 0.4.

* The quantity which we have here called "force of pressure" is frequently called "total pressure," or simply "pressure"; but as a matter of fact it is a force and not a pressure.

For any two given substances having fairly smooth surfaces in contact the coefficient of friction is nearly constant. Thus, for wrought iron rubbed against wrought iron, the coefficient is about 0.14; for wrought iron rubbed on cast iron, it is about 0.20. For iron sliding on ice (skates), its value is as low as 0.02 or 0.03.

It has been found by experiment that friction is very little affected, either by the speed of the motion, or by the area of the sliding surfaces. A small brake shoe is just as effective in stopping a car as a large one, but will, of course, wear out sooner. It must, however, be remembered that these statements are true only within limits. If, for instance, one body be so narrow as to cut into the other, the laws just stated are no longer applicable.

When a wagon or sled is pulled along a level road at a uniform speed, it is well known that *the vehicle exerts no force backward except when it is in motion forward.* In overcoming friction, therefore, we must always exert a force through a distance, or, in other words, we must always do work. Friction is, therefore, an almost omnipresent force which is continually wasting, though never destroying, energy. Friction demands that we shall always put more work into a machine than we can ever get out of it. Hence the impossibility of any perpetual motion machine and hence also the resolution of the French Academy in 1775 not to receive any further communications on this subject.

Exercise 23. — Coefficient of Friction

References. — Hall and Bergen, Chap. VI.; Avery, 126–127; Wentworth and Hill, 35–38.

Apparatus. — Smooth pine board, from 8 to 12 inches wide and 3 or 4 feet long; smooth block of pine wood, say $2 \times 4 \times 6$ inches, with a screw eye for attaching a cord; rectangular piece of sheet brass, say 6×3 inches, with one end bent up a little, and a hole drilled in the upturned end to receive a

cord; spring-balance graduated in grammes; set of weights. Five or six half-kilogramme masses will do well.

Problem. — A study of some of the forces which transform mechanical energy into heat energy; in particular, a verification of the laws of friction.

Experiment. — (*a*) Weigh the block on the spring-balance, and record its mass.

(*b*) Fasten the hook of the balance to the block with a cord. Lay the block on the board, and place on it a mass of not less than 1 kg. This mass is merely to increase the weight on the board, since the friction might otherwise be too small to be measured accurately. Record the combined weight of the block and its load.

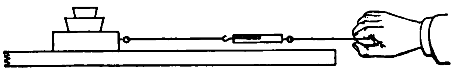

Fig. 32. — Measurement of friction.

(*c*) By pulling on the balance draw the block along the board slowly, and with uniform motion. Keep the cord and balance horizontal. Read the balance *while the block is moving uniformly*. The balance reading will probably vary somewhat, since the board is not equally smooth at all points. Take your reading at a time when the index is most nearly steady. Make at least three trials, record the readings, and take their mean as the force of friction.

(*d*) Now increase the weight on the block, and repeat (*b*) and (*c*). Use at least five different weights.

(*e*) In each experiment compute the coefficient of friction by dividing the force of friction by the force with which the lower surface of the block is pressed against the surface of the board. This latter force is, of course, the weight of the block plus the weight of the load on it.

(*f*) Repeat (*a*), (*b*), (*c*), (*d*), and (*e*), using the brass plate instead of the wooden block, and so find the coefficient of friction between brass and pine.

Why do engine builders use bearings in which brass rubs on steel, instead of steel on steel?

Record your results in the following form:

Substances rubbed together	Total weight of block and load (W)	Friction				Coefficient of friction $\left(\frac{F}{W}\right)$
		Trial 1	Trial 2	Trial 3	Mean (F)	

(*g*) Test the effect of changing the area of the surfaces in contact. Find the friction with the block first on its flat side, then on the narrow edge, putting on the *same load* in each case.

How do the areas in contact compare in these two cases? How do the corresponding values of the friction compare?

Exercise 24. — The Inclined Plane

References. — CREW, 78; CARHART AND CHUTE, 121–122; AVERY, 140–141; WENTWORTH AND HILL, 46; GAGE, 83; HALL AND BERGEN, 67–69.

Apparatus. — An inclined plane such that the inclination can be varied. The plane may well be provided also with a slot running lengthwise through the middle of it, so that the force may be applied parallel to the base; a small carriage or roller running with small friction; a spring-balance; a scale suitable for measuring lengths on the inclined plane.

Problem. — To apply the principle of the Conservation of Energy to the inclined plane.

Experiment. — (*a*) Having set the inclined plane at a definite angle, measure the amount of force required to just pull the carriage up the inclined plane when the direction of the pull is parallel to the inclined plane. The amount of this pull can be measured by either of the two following methods, namely, by holding the spring-balance in a line parallel to the inclined plane, having attached the carriage to the hook of the

spring-balance, or by hanging a scale pan over the pulley (Fig. 33), having connected the scale pan and the carriage by means of a string. Put weights in this scale pan until the carriage is just pulled up the plane. Now take weights out of the scale pan until the carriage just begins to run down the plane. The mean between these two forces will be the force required. Call this *P*.

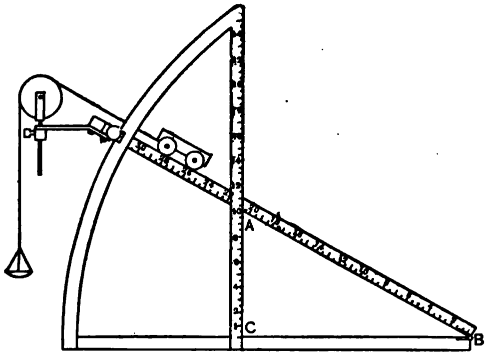

Fig. 33.—The inclined plane.

(*b*) Measure by means of a spring-balance or by an ordinary beam-balance the weight of the carriage and any load it may have had in it. Call this *W*.

(*c*) Measure by means of a scale any length, *AB*, on the inclined plane. Call this *l*.

(*d*) Now measure the vertical distance from *A* to *C*, where *C* is a point *on the same level* with *B*; call this distance *h*.

Having made these four measures, record them in a table as follows:

Weight, W	Force parallel to plane, P	Length of Plane, l	Height, h	Work, $P \times l$	Work, $W \times h$
g.	g.	cm.	cm.		
575	202	19.3	6.9	3899	3968
575	125	18.5	4.1	2313	2358
575	61	18.1	2.0	1104	1150

Compute the work done by the force *P* when exerted through a distance *l*, and record in column 5. Compute the work required to lift the weight *W* through a distance *h*, and record

this in the last column. How do these two compare in value? Explain.

(*e*) Repeat this experiment for two other angles of slope.

Exercise 25. — The Pulley

References. — CREW, 75, 77; ROWLAND AND AMES, 49; AVERY, 137–139; WENTWORTH AND HILL, 39, 212; CARHART AND CHUTE, 118–120; GAGE, 77.

Apparatus. — Two small pulleys, well centred, and having as little friction as possible. At least one of the pulleys should be double, *i.e.* should have two sheaves; the other may be single. Set of weights, say, from 100 to 500 g.; scale pan; spring-balance graduated in grammes; retort stand, or other support for the pulley; cord.

Problem. — To find the mechanical advantage of several different combinations of pulleys.

Experiment. — (*a*) With the spring-balance, find the mass of the scale pan. Also find the combined masses of the scale pan and the single pulley, and of the scale pan and the double pulley.

(*b*) *Fixed Pulley.* — Suspend the single pulley from the support. Pass a cord over it, attaching the scale pan to one end, and the spring-balance to the other, as in Fig. 34. Put a known mass on the pan. Pull vertically downward on the balance, and note the force necessary to raise slowly the loaded pan. Also note the force indicated by the balance while the pan slowly descends. There will always be some friction at the pulley. While you lift the pan, this friction increases the balance reading; but when the pan descends, it decreases the balance reading. The mean of the two readings should then be the force necessary to hold in equilibrium the loaded pan, the effect of friction having been

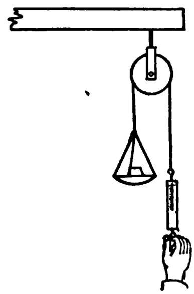

FIG. 34. — Mechanical advantage of fixed pulley.

eliminated. Repeat the experiment with masses of 100, 200, 300, 400, 500 g.

If we call the total weight of the pan and its load F_2, and the mean force exerted by the spring-balance F_1, the mechanical advantage of any pulley system is $\frac{F_2}{F_1}$. Compute the mechanical advantage. How does the number representing the mechanical advantage compare with the number of cords (in this case, one) supporting F_2?

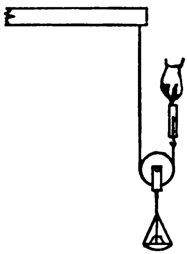

Fig. 35. — Mechanical advantage of movable pulley.

(*c*) *Movable Pulley.* — Arrange a pulley system as shown in Fig. 35. Determine the mechanical advantage, as in (*b*). Here F_2 is supported by *two* cords. How does this number compare with the number representing the mechanical advantage?

(*d*) Arrange a pulley system in which the load F_2 is supported by *three* cords. This may be done by using two fixed pulleys (double pulley), and one movable pulley. (See Fig. 36.) Find out for yourself the proper arrangement of the cord. Determine the mechanical advantage as in (*b*). Of what use is the uppermost of the three pulleys?

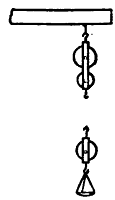

Fig. 36. — Mechanical advantage of combination of pulleys.

(*e*) Devise a pulley system in which *four* cords support the scale pan. Determine the mechanical advantage for this system, using different masses, as in (*b*).

In each of these cases, how does the gain of potential energy of the raised weight compare with the work done in raising it?

Record your data in the following form:

Mass of scale pan	=	grammes.
Mass of scale pan and single pulley	=	grammes.
Mass of scale pan and double pulley	=	grammes.

Weight in pan	Total weight (F_2)	Balance reading			Mechanical advantage $\frac{F_2}{F_1}$	Number of cords supporting F_2
		raising	lowering	mean (F_1)		

N.B. In your report, explain the four pulley systems by means of *sketches*, instead of by written descriptions.

SECTION 3.—ILLUSTRATION OF GRAVITATION

Exercise 26.—Simple Pendulum

References.—Crew, 88; Hall and Bergen, 85; Rowland and Ames, 31; Carhart and Chute, 96–105; Wentworth and Hill, 189–191; Avery, 112–120; Gage, 60–61.

Apparatus.—Pendulum, made of a wooden or metal sphere, suspended by a fine thread; a bullet answers well, if provided with a short loop of fine wire or with a small tack driven into it, for attaching the thread; a clamp of some kind, for supporting the pendulum. One of the flat-jawed clamps devised by Professor Stratton, and made by Gaertner, is very convenient for this purpose. (See Fig. 37.) Clock beating seconds, or stopwatch; metre stick.

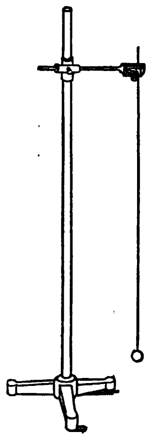

Fig. 37.

Problem.—To find how the period of a pendulum varies with the length of the pendulum, a study of the acceleration of gravity.

Experiment.—(*a*) In a pendulum like the one described above, "the length" is very nearly the distance from the point of support to the centre of the sphere. Fix the thread in the clamp so

that the length shall be about 100 cm. With the metre stick, measure the length carefully, and record it.

(*b*) Now set the pendulum swinging through a small arc, — not more than $\frac{1}{20}$ of the length of the pendulum. Sit where you can easily see the pendulum and the clock face without turning your head. Note carefully the position of the second-hand at the instant the pendulum passes through its position of rest in a given direction, say from left to right. Call this the 0th vibration. At the *next* passage through this point in the same direction, count "one"; and so on up to 50 vibrations. Finally note the position of the clock hand at the instant the 50th vibration is finished. The difference between the clock readings will be very nearly the time occupied by your pendulum in making 50 vibrations. Divide this length of time by 50, and so obtain the number of seconds required for one vibration. This length of time is called the **period** of the pendulum.

If a stop-watch is used, instead of a clock, start the watch on any passage of the pendulum through its position of rest. Count the succeeding passages of the pendulum through this position, and stop the watch on the 50th succeeding passage.

(*c*) Make a second determination of the length of time required for 50 vibrations, as in (*b*). This should agree very closely with the first determination. The difference ought to be less than one second. Compute the period from the second observation. Take the mean of the two determinations as the period of the pendulum.

(*d*) Repeat (*a*), (*b*), and (*c*), using different lengths of pendulum. These lengths may be about as follows: 100, 75, 60, 50, 40, 30, 20, 10, and 5 cm. Record your data in tabular form, as shown below.

(*e*) In the last column of the table enter the quotient found by dividing each length by the square of the corresponding period. Do you notice anything unusual about the numbers so obtained? When you find two quantities such that their ratio is constant, you know that one of these quantities varies directly as the other. To what, therefore, is the period of a

pendulum proportional, at any given place on the earth's surface?

(*f*) Taking lengths of the pendulum as abscissas, and the corresponding periods as ordinates, plot a curve. Does the form of this curve give you any information as to the manner in which the period of a pendulum varies with its length?

Length of pendulum (l)	Time of 50 vibrations			Period (T)	$\frac{l}{T^2}$
	Trial 1	Trial 2	Mean		
cm.	sec.	sec.	sec.	sec.	
100					
75					
etc.					

Mean =

(*g*) Having found the mean of the numbers in the last column, use this to compute g, the acceleration of gravity, by the formula (see Crew's *Elements of Physics*, Art. 88, Eq. 8″),

$$g = \frac{4\pi^2 l}{T^2}.$$

SECTION 4. — ILLUSTRATION OF ELASTICITY

Exercise 27. — The Spring-balance — Hooke's Law

References. — Crew, 111; Rowland and Ames, 55, 60; Wentworth and Hill, 25.

Apparatus. — A light spiral spring made of brass wire which is a little less than 1 mm. in diameter. The spiral should have a diameter of from $1\frac{1}{2}$ to 2 cm. The length of the spiral when closely coiled may well be about 10 cm. The spring should be supported by an upright, as indicated in Fig. 38. A scale pan is carried at the lower end of the spring; and back of the spring, on the upright, should be a millimetre scale. Set of ordinary weights running from 1 to 200 g.

A Jolly balance furnishes a convenient instrument for this

experiment, but the spring should be replaced by one stiffer than those usually employed for specific gravity determinations with the Jolly balance. The stiffer spring allows the use of heavier masses, which are more easily handled and less liable to loss.

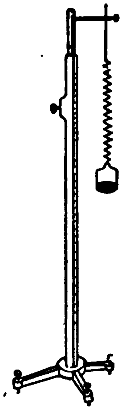

FIG. 38. — Verification of Hooke's Law; case of spiral spring.

Problem. — To find how the elongation of a spiral spring varies with the stretching force; a study of elasticity.

Experiment. — (*a*) Adjust the upright so that the spring hangs as nearly as possible parallel with the scale.

(*b*) Hang the scale pan on the hook at the lower end of the spring and read, as accurately as possible, the point on the scale which lies just opposite the upturned end of the hook. (Any other definite point on the scale pan, or on the end of the spring, will serve equally well as an index.) Call this the "zero-reading" of the balance.

(*c*) Now place on the pan a mass of 5 g., and read the position of the index. The difference between this reading and the zero-reading is the *elongation* produced *by the weight of 5 g.* Each different load that we put on the pan produces a different elongation. When the load is doubled, is the elongation doubled? To answer this question put 15 different loads on the pan and observe the elongation produced by each load. Record your results as indicated in the accompanying table. . In the third column of this table, compute the elongation due to each load. In the last column, compute the ratio between the load and elongation.

Obs.	Load on pan	Reading of index	Elongation (computed)	Ratio of load to elongation
1 etc. 15				

(*d*) Plot a careful curve expressing the same results which you have recorded in your table. Use "loads" as abscissas and "elongations" as ordinates.

What is the difference between the length of a wire carrying a load of 5 g. and the elongation of a wire due to a load of 5 g.? What do you consider the greatest source of error in these measurements? What is the fact which is described by "Hooke's Law"?

What test of the truth of Hooke's Law for this spring is furnished by your tabulated results? What test is furnished by the curve?

CHAPTER III

SPECIAL PROPERTIES OF MATTER

SECTION 1. — ILLUSTRATIONS FROM HYDROSTATICS

Exercise 28. — The U-tube Manometer — Balancing Columns

References. — CREW, 121, 123, 137, 140; ROWLAND AND AMES, 68–69; AVERY, 146–152; HALL AND BERGEN, 205.

Apparatus. — A U-tube, as in Fig. 39, made of tubing of about 1 cm., inside diameter, with arms about 40 cm. long; the bent tube to be mounted on a vertical board, or held in a clamp; millimetre scale ½ m. or more in length; piece of rubber tubing not less than 3 feet long; pinch-cock; kerosene.

Problem. — To learn a simple method of measuring pressures; a study of some of the fundamental properties of fluids, involving another method for measuring specific gravity.

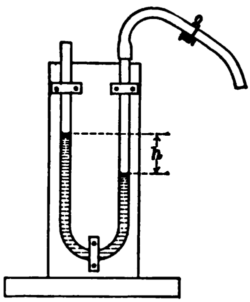

Fig. 39. — **A simple form of pressure gauge.**

Experiment. — (*a*) Pour some water into the U-tube. How does the height of water in the left arm compare with that in the right arm? How do the pressures of the atmosphere upon the two surfaces of the water compare?

(*b*) Increase or decrease the quantity of water until each arm is about half full. Attach a piece of rubber tubing to one end of the U-tube. Over the rubber tube slip a pinch-cock. Blow gently into the rubber tube until the surface of water in one arm is 15 or 20 cm. higher than in the other. Before the pressure is relieved, close the pinch-cock. Measure the height

of each surface of the water above some fixed horizontal surface, such as the table-top, or the wooden base of the apparatus. The difference between these heights (h, Fig. 39) is called the "difference of level," or simply the **head** of water; and this head represents the difference between the pressure of the enclosed air and the pressure of the air in the room, expressed in centimetres of water.

(*c*) Attach the free end of the rubber tube to the gas-pipe, and measure the pressure of the gas in centimetres of water.

(*d*) Pour out a little water, until each arm is about one-third full. Into one of the arms pour kerosene to within three or four centimetres of the top of the tube. What happens to the water? The difference of level of water now serves to measure the pressure exerted by the column of kerosene, just as it previously measured the pressure of air or of gas. Measure the heights of the water surfaces, and thus find the pressure exerted by the kerosene in centimetres of water.

(*e*) Measure also the height of the top of the kerosene column. How long is the column of kerosene which exerts the same pressure as the head of water? According to this, is kerosene more or less dense than water? What is the ratio between their densities? If the density of water is unity, what is the density of kerosene? A U-tube used for measuring pressures by the difference of level of the liquid contained in it is called a **manometer**, which is simply a Greek word for "pressure gauge."

Exercise 29. — The Siphon

References. — Crew, 72, 116–123; Carhart and Chute, 155–159; Rowland and Ames, 80; Avery, 170–171.

Apparatus. — Two beakers, or tumblers, from 4 to 6 inches in height; a siphon with equal arms, each about 8 inches long; another siphon of which one arm is 2 or 3 inches shorter than the other. These siphons may well be made of glass tubing which has a bore lying between $\frac{1}{8}$ and $\frac{1}{4}$ of an inch. Some half-dozen blocks of pine board upon which to set the beakers.

Problem. — To study the conditions under which a liquid will flow from one vessel to another, and to illustrate the laws of the siphon. To illustrate also the general principle that the potential energy of a system tends to a minimum.

Experiment. — (*a*) Fill one beaker with water and leave the other empty; support each beaker upon a pile of two or three blocks. Take a U-tube which has arms of *equal* length and fill it with water, either by holding it under the tap or by dipping it into a bucket of water. Stop the ends with your fingers, invert the U-tube with one arm in one beaker and the other arm in the other beaker. Note what happens to the water. When the water has ceased to flow, how do the levels in the two vessels compare?

(*b*) Now slip a block from under one beaker. What happens in the U-tube? A tube used to transfer liquid in this way from one vessel to another is called a **siphon.**

(*c*) Fill one beaker with water and place it on blocks so that it stands, say 4 or 5 inches higher than the other. Next fill with water a siphon which has arms of *unequal* length. Place your fingers over the ends and invert the tube over the beakers so that the long end dips into the beaker containing the water. It is well at this point in the experiment to hold the siphon in a clamp, else the end of the short arm will not have a definite height. Presently the water will stop flowing out through the siphon. When this occurs, how high is the level of the water in the upper vessel compared with the end of the short arm?

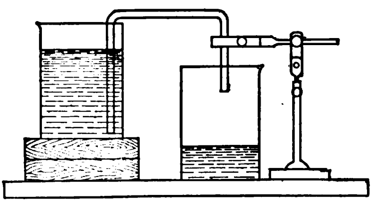

FIG. 40. — The siphon.

Let us consider the system made up of the two beakers of water and the siphon. After the flow has stopped, in any case, is the potential energy of the system greater or less than before the flow began?

(*d*) Consider the highest point in the U-tube while the water is running from one vessel to the other. On which side of this point is the pressure in the tube greater? Make a diagram of the condition of affairs when the water ceases to flow from one vessel to the other. In your report give a brief explanation of the siphon.

Exercise 30. — Illustration of Archimedes' Principle — Floating Bodies

References. — Crew, 124; Rowland and Ames, 64; Carhart and Chute, 163, 168; Avery, 153–154; Wentworth and Hill, 72–74.

Apparatus. — Three or four slender rods of light wood, about a foot in length, with their ends sawed off square; they may be either rectangular or circular in cross-section, but must be carefully shaped, so that each shall have a uniform area of cross-section; but no two should have the same area of cross-section; bore a hole in the end of each and fill it with melted lead or a close-fitting piece of brass rod, adding in this way rather more than enough ballast to make the rod float upright in water; the hole must be filled flush with the surface, either with the ballast itself, or with putty; beginning at the bottom of each rod, graduate one side of it in centimetres, with sharp lead pencil marks, throughout its length; then soak the rods in melted paraffin to render them impervious to water. Jar of water deep enough to float the sticks; vernier caliper; set of weights; balance.

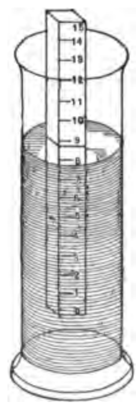

Fig. 41.—Equilibrium of floating bodies.

Problem. — To show that a body floating in water displaces its own weight of water; a special case of Archimedes' principle, which states that the loss of weight of a body placed in a fluid is equal to the weight of the fluid displaced.

Experiment. — Perform the following series of operations with each rod in turn.

(*a*) Float the rod in water. Read off the depth to which it sinks, estimating this depth to one-tenth of a centimetre.

(*b*) If the section of the rod is circular, measure the diameter in several places with the vernier caliper; if the section is rectangular, measure the width and thickness of the rod in several places. Calculate the area of cross-section at each place measured, and find the average area of cross-section of the rod.

(*c*) Hence, compute the volume of the immersed portion of the rod. What is the weight of the water which the rod displaces while floating?

(*d*) Weigh the rod on a balance, first drying it. How does its weight compare with the weight of water displaced?

(*e*) Float the rod again. Place on its flat top about as much weight as can be added without causing the rod to upset or sink below the surface. Read off the depth to which the rod is now immersed. Hence find the weight of water displaced, as above, and compare this with the total weight of the rod, including its load.

Record your data in tabular form, under the following headings. Average area of section; length immersed; volume of displaced water; weight of displaced water; weight of rod plus load; $\frac{\text{wt. of rod and load}}{\text{wt. of displaced water}}$. How much of its weight does a body appear to lose when floating in water? What, then, is the apparent weight of a floating body? Under what circumstances may the apparent weight of a body be said to be negative? Why does an empty stoppered bottle float, even though glass is much denser than water?

DENSITY AND SPECIFIC GRAVITY

Sometimes on picking up two blocks of wood of the same size we are surprised to find how much heavier one is than the

other; so with two books of the same size we often find one much heavier than the other. And often in handling a single block or a single book we say "This is very heavy," or "This is extremely light," as the case may be. But evidently what is here meant is that the block is "heavy" when we consider its volume; or in other words, the ratio of its mass to its volume is large.

This *ratio of mass to volume* is such an important and frequently used quantity that it has been given a name of its own. It is called **density**.

Its defining equation would then read,

$$\text{Density} = \frac{\text{Mass of a body}}{\text{Volume of that body}}$$

or

$$D = \frac{M}{V}.$$

Problem. — If 432 cubic inches of water weigh 15.8 pounds, what is the density of water, when you measure volumes in cubic inches and masses in pounds? What is the density of water when you measure volumes in cubic feet and masses in pounds? Enter this result in the margin of this page. What value has the density of water when you measure volumes in cubic centimetres and masses in grammes?

But there is another method besides the one which we have just considered for expressing the fact that there is little or much matter in any given volume. This method consists in stating how much matter there is in any volume compared with the matter in an equal volume of water.

This ratio is known as the **specific gravity** of the substance. Its defining equation is

$$\text{Specific gravity} = \frac{\text{Mass of any body}}{\text{Mass of an equal volume of water}}.$$

Now the density of water is a well-known quantity; and for all practical purposes may be taken as unity. Hence we can easily find the mass of any volume of water. And hence this ratio will tell just how much matter there is in any body of given volume as soon as we know its specific gravity.

Problem. — (1) The specific gravity of brass is 8. What is the volume, in cubic centimetres, of 32 grammes of brass?

(2) The specific gravity of glass is 2.5. How many pounds will 1 cubic foot of glass weigh?

(3) Does the value of *specific gravity* depend upon the unit of volume which you employ?

(4) Does it depend upon the unit of mass which you employ?

Show, by using the defining equations given above, that

$$\text{Specific gravity of any substance} = \frac{\text{Density of that substance}}{\text{Density of water}}.$$

Exercise 31. — Illustration of Archimedes' Principle — Hydrostatic Balance

References. — Crew, 124; Gage, 113; Carhart and Chute, 173–174.

Apparatus. — Balance, with wooden bench, on which a vessel of water may be supported over the pan, without touching it (see Fig. 42); set of weights; beaker of water; about four specimens of solid substances, which are heavier than water, and do not dissolve in it; such as pieces of glass, aluminium, brass, or quartz; select fairly large pieces, 100 g. or more, and use at least two pieces of each substance of quite different sizes; fine, strong thread.

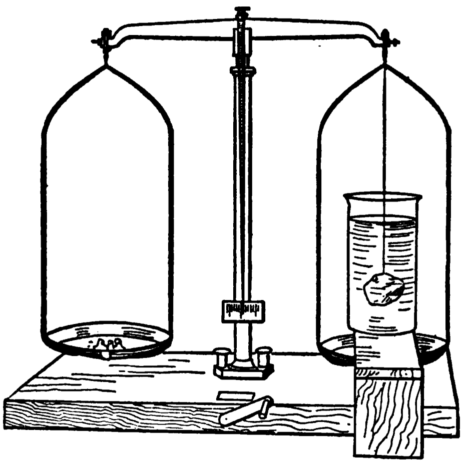

Fig. 42. — "Upthrust" of a fluid on a solid immersed in it.

Problem. — An application of Archimedes' principle to the measurement of specific gravity.

Experiment.—*Part 1.* (*a*) Suspend one of the bodies by a short piece of thread from the hook of the balance, or place the body and thread in the pan and weigh them. If the weight of the thread is small enough to be neglected, this process will give you the weight of the solid body, *expressed in terms of the weight of a gramme-mass.*

(*b*) Now support a beaker of water on the bench directly over the pan. Let the solid, suspended from the hook, be completely immersed in the water. See that the solid does not touch the beaker. Carefully remove any bubbles that may have formed on the solid. Now weigh again. You will find the weight less than before. This "loss of weight" is due to the water, which supports part of the weight, thus exerting an "upthrust" upon the solid. The process just described is called "weighing in water." It is to be carefully noted that the water itself is not placed upon the balance pan, and, in fact, forms no part of the balance system. If both the water and the solid immersed in it were weighed together, there would have been no "loss of weight."

(*c*) Archimedes' principle tells us that the upthrust of a fluid on a body wholly immersed in it is equal to the weight of the fluid displaced by the solid. That is, the upthrust is equal to the weight of a portion of the fluid having the same volume as the solid. Compute the upthrust, and hence the weight of the water having the same volume as the solid which you are using.

(*d*) The specific gravity of any body may be defined as the ratio of the weight of that body to the weight of an equal volume of water. Calculate the specific gravity of each of the bodies furnished you, using at least two specimens of each substance.

Part 2. Further study of Archimedes' principle.

(*a*) Place the beaker of water on the balance pan, and weigh it.

(*b*) Immerse one of the solids in the water, supporting it from an arm extending over the beaker, but not forming a part

of the balance, as shown in Fig. 43. Weigh the beaker of water with the solid immersed in it. You will find that it has gained in weight.

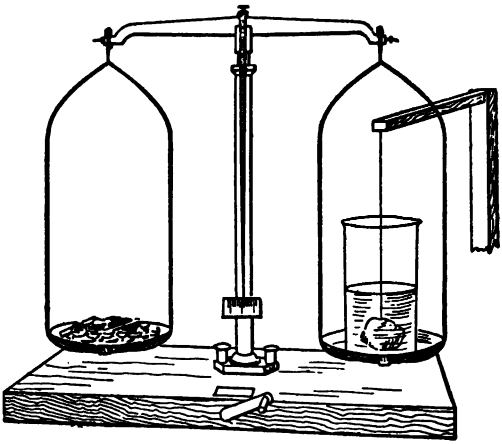

FIG. 43. — "Downthrust" of a solid on the fluid surrounding it.

How does the "downthrust" of the solid upon the water compare with the "upthrust" of the water on the *same* solid as determined in Part 1 of this exercise? What becomes of the weight lost by a body immersed in water?

(*c*) Repeat this experiment, using in turn each of the solids employed in Part 1. It will of course be necessary to weigh the beaker of water each time, as the amount of water in it is diminished whenever a solid is taken out. Could the specific gravity of a solid be found by the method employed in Part 2 of this experiment? How many weighings would be necessary?

Record all your results in tabular form.

Exercise 32. — Nicholson's Hydrometer

References. — CREW, 124; AVERY, 157; WENTWORTH AND HILL, 75.

Apparatus. — Nicholson's hydrometer; tall jar to contain water; three small bodies whose specific gravities are to be determined; slotted cardboard to cover jar; set of weights running from 10 mg. up.

Problem. — To measure the force which a liquid exerts upon a body immersed in the liquid; and thus, to determine the specific gravity of the body; a further study of Archimedes' principle.

Experiment. — Nicholson's hydrometer is simply a floating body, usually made of glass or copper, and weighted at one end so that it will stand upright in a liquid. (See Fig. 44.)

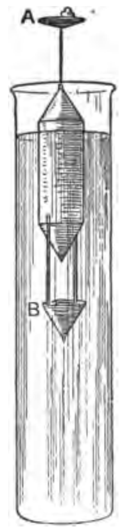

Fig. 44. — The hydrometer, invented by Boyle, and improved by Nicholson.

In water this hydrometer will float with its neck some distance above the surface. The position which the hydrometer takes is such that its weight is just counterbalanced *both in direction and in amount* by the upthrust of the water.

Cover the jar with a piece of cardboard, slotted so as to admit freely the stem of the hydrometer into the slot. This cardboard will prevent the weights from falling into the water and the hydrometer from sinking.

(*a*) Now place weights in the upper pan until the index marked on the stem sinks to the surface of the water. How much greater is the weight of liquid now displaced than before these weights were added? This weight, which is required to sink the hydrometer to its index, we shall call A.

(*b*) Having removed the weights from the upper pan, place in it a piece of glass, whose specific gravity you wish to measure. Now add to the upper pan weights which, together with the glass, are just sufficient to again sink the hydrometer to its index. Call the weight which you have added B. What is the weight of the glass in terms of A and B? This question should be distinctly and clearly answered before you proceed with the experiment.

(*c*) Now place this same piece of glass in the lower pan, and put weights into the upper pan until the hydrometer again

sinks to its index. Denote by C the weights which are now in the upper pan. Is the weight of the glass in water greater or less than its weight in air? What is the weight of the glass in water in terms of A and C? This step should be perfectly clear before you proceed.

Caution. — Remove air bubbles from the body in water. If they are not removed, will they make your result too large or too small?

(*d*) *Computation.* — You have now found the weight of the piece of glass in air, also its weight in water. From these you can obtain, by subtraction, *the loss of weight* which the glass suffers when immersed in water. And, by Archimedes' principle, we know that this loss of weight is the same as the weight of a volume of water equal to that of the glass.

Let us put The weight of the glass $= W_g$,

and The weight of an equal volume of water $= W_w$.

Then, since

$$\text{Specific gravity} = \frac{\text{Weight of body}}{\text{Weight of equal volume of water}},$$

we may write,

$$\text{Specific gravity} = \frac{W_g}{W_w} = \frac{A - B}{C - B}.$$

In this manner measure the specific gravity of at least three different substances, recording your results in a table, under the headings, "Substance," "A," "B," "C," "A − B," "C − B," "Specific Gravity." Do not be satisfied with one measurement of A, but repeat it carefully for each different substance.

This method of determining specific gravities was invented by Robert Boyle, in 1675, and improved by Nicholson, an English physicist. (See Appendix A.)

Exercise 33. — Specific Gravity of a Solid by Spring-balance

References. — Crew, 111, 124; Avery, p. 178.

Apparatus. — A spiral spring made of about 100 turns of brass wire, wound in a coil having a diameter of approxi-

mately 1 inch. If the wire is $\frac{1}{2}$ mm. in diameter, the weight of 1 g. will elongate the spring about 2 cm. Something like

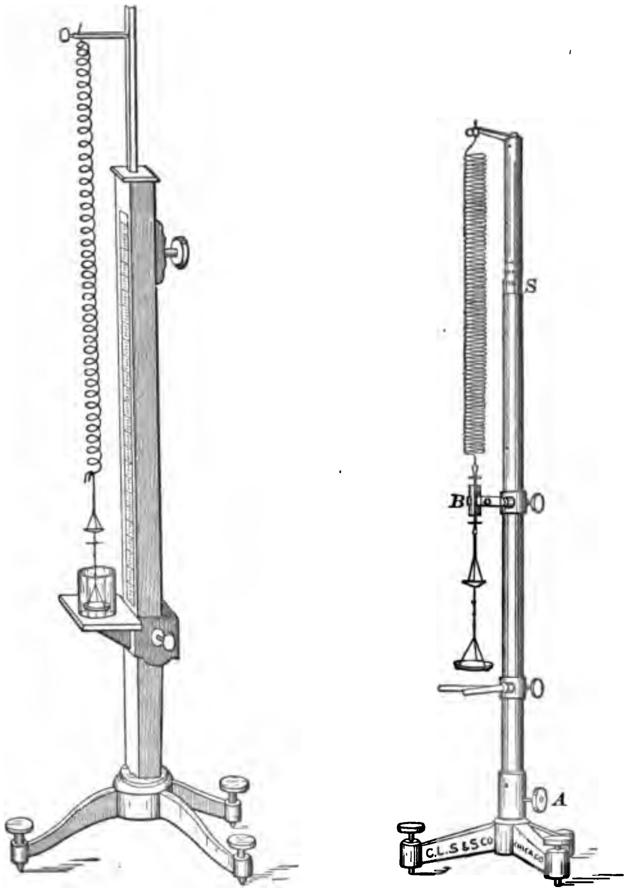

Fig. 45.—Two forms of the Jolly balance.

this degree of sensibility will be found convenient for ordinary work. The spring should be supported on an upright, as indicated on the left in Fig. 45. This upright should have

attached to it a scale, preferably one ruled on a mirror, and one on which the marks are fine and easily read; two small scale pans, supported by the spring, one vertically above the other; tumbler of water at temperature of room; three small bodies whose specific gravities are to be determined, such as glass, sulphur, porcelain, brass, aluminium.

A most excellent balance of this type, embodying several improvements upon the usual form invented by Jolly, is that devised by Mr. C. E. Linebarger, and made by the Chicago Laboratory Supply and Scale Company, as shown on the right in Fig. 45.

Problem. — To study the spiral spring as an instrument for measuring forces, and to employ the principle of Archimedes to determine the specific gravity of a solid substance.

Experiment. — (*a*) The first step is to see that your balance is in good working order. The scale should be placed in a vertical position so that it will be parallel to the spring. The lower pan should be supported from the upper one by a single strand of very fine wire, as indicated in Fig. 46. See that the pan does not touch the side of the beaker holding the water. *All readings of the position of the index are to be taken with the lower pan immersed in water.* Therefore, especial care must be used to see that when the lower pan is under water *only one wire*, not three, cuts the surface of the water. And equal care must be used not to get the upper pan wet, or, if the pan does get wet, to dry it at once.

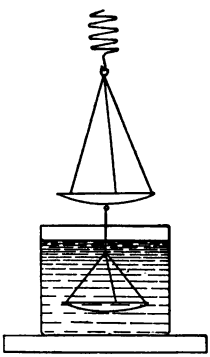

Fig. 46. — Showing the two pans of a Jolly balance.

(*b*) Let us suppose that you have adjusted the instrument. You are now ready to use it as a balance. It is, indeed, the same kind of a balance as that used in the meat market, only here the scale is straight, not circular. As we have already found (Exercise 27), each gramme

which is added to the pan elongates the spring by the same amount. To weigh a body we have, therefore, only to place it in the *upper* pan and measure the amount by which the spring is stretched. To measure this stretch, one must, of course, make two readings: first, a zero-reading, that is, a reading when there is no load in the pan; call this reading A. And then a second reading must be made when the body is in the upper pan; call this reading B.

After making the zero-reading, hold the pan while you place the body in it; and lower the tumbler until the *lower* pan is immersed in water to the same point as before. The difference between these two readings, $B - A$, will give you *the weight of the body in air.* In what unit is this weight expressed?

(*c*) Take the same body whose weight in air you have measured and proceed to weigh it in water. This weighing is done exactly as the preceding, except that the body is now placed in the lower pan. The tumbler must now be raised until the lower pan is immersed in the water to the same point as before. Let us denote by C this third reading, which is taken when the body is in the lower pan. The loss of weight in water is $B - C$. But, by the principle of Archimedes, this loss of weight is the weight of a volume of water equal to the volume of the body, and since

$$\text{Specific gravity} = \frac{\text{Weight of body in air}}{\text{Weight of equal volume of water}},$$

we have

$$\text{Specific gravity} = \frac{B - A}{B - C}.$$

Caution. — Be careful to remove any air bubbles that may collect on the body, or on the scale pan, immersed in water.

(*d*) Repeat this experiment for at least two more solid bodies. Record your observations in a table under the following headings: "Substance"; "Zero-reading, A"; "Reading, body in

upper pan, B"; "Reading, body in lower pan, C"; "Weight of body, $B-A$"; "Weight of water displaced, $B-C$"; "Specific gravity, $\frac{B-A}{B-C}$."

This method of measuring specific gravities was perfected by the late Professor Jolly, of the University of Munich. His form of balance may be obtained from Berberich, of Munich.

Exercise 34. — Specific Gravity of a Liquid by Spring-balance

References. — Crew, 111, 124.

Apparatus. — Same as that employed in the immediately preceding exercise, except that, for the two pans, one substitutes a glass "sinker," having a form somewhat like that indicated in Fig. 47; and, instead of solid bodies, it will be necessary, of course, to provide a beaker, or, better still, a short test-tube of the liquid to be measured. It is convenient to have on hand two or three "stock solutions" of copper sulphate, the densities of which have already been determined, and from which portions may be distributed to students for measurement. A hole bored in a small block of wood makes a convenient support for the test-tube, as shown in Fig. 47.

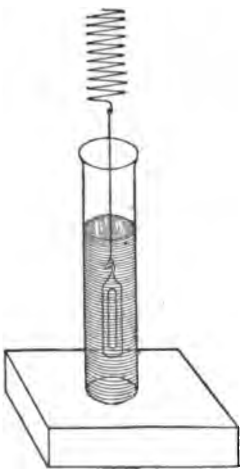

Fig. 47. — Form of glass sinker used in Jolly balance.

Problem. — To study the spiral spring as an instrument for measuring forces; and to employ the principle of Archimedes to determine the specific gravity of a liquid substance.

Experiment. — For any given liquid, say a solution of table-salt, this process involves two steps, namely: (1) the measurement of the loss of weight which the sinker suffers when immersed *in the salt solution*, and (2) the measurement of

the loss of weight which the sinker suffers when immersed *in water*. Knowing these two, we have, by Archimedes' principle,

$$\text{Specific gravity of salt solution} = \frac{\text{Loss of weight in salt solution}}{\text{Loss of weight in water}}.$$

(*a*) Read the position of the index when the sinker, cleaned and dried, hangs freely in air. Call this reading A.

(*b*) Bring underneath the sinker a test-tube of salt solution, or of copper sulphate solution, and raise this until the sinker is immersed in the solution up to a certain point on the supporting wire. Call this index reading B. What is the physical meaning of $A-B$, that is, what weight does $A-B$ represent?

(*c*) Bring underneath the sinker a test tube of water, and again read the index on the end of the spring when the sinker is immersed. Call this reading C. What is the physical meaning of $A-C$?

Tabulate your results under the following heads:

"Substance," "A," "B," "C," "$A-B$," "$A-C$," "$\frac{A-B}{A-C}$."

SECTION 2. — ILLUSTRATIONS OF SURFACE TENSION

Exercise 35. — The Phenomena of Surface Tension

References. — Crew, 125–128; Rowland and Ames, 72–73; Carhart and Chute, 27–35; Hall and Bergen, 190–195; Avery, 46, 48; Wentworth and Hill, 145.

Apparatus. — A slender glass rod about 1 foot long; a glass tumbler and a small dish or pan to hold water; a Bunsen flame or an alcohol lamp; two matches or wooden toothpicks; a small bit of any ordinary soap.

Problem. — A qualitative study of the forces which make their appearance only at the bounding surface of a liquid.

Experiment. — (*a*) Take a piece of glass rod, a quarter of an inch or less in diameter, and a foot or so in length. If one end of the rod be dipped into a tumbler of water, you observe that a drop of water hangs on the end of the rod. Sketch in your note-book the exact appearance of the rod and drop just before the drop falls off.

(*b*) Take a tumbler of water in one hand and the glass rod in the other. By holding the glass rod against the edge of the tumbler, try to pour the water slowly from the tumbler into another vessel without allowing the water to spill or to splash. Chemists often use a glass rod in this way instead of a funnel. How do you explain the fact that the water hugs the rod closely, as if it were flowing down the inside of a tube? It will be wise for you to have a conversation with your instructor before you write out an answer to this question.

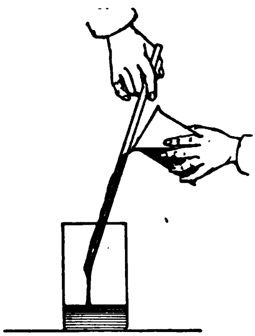

FIG. 48. — A liquid surface used as a funnel.

(*c*) Now take the glass rod and dry it carefully. Choosing one end which has a sharp fracture, hold this end in a flame until it begins to soften. Examine the end from time to time, and you will observe that the sharp edges of the fracture are now becoming rounder and rounder. As the sharp edges of the glass disappear, does the surface of the glass increase or diminish in area?

(*d*) Take a wooden toothpick or the stick of a match and break it in two. Float these two bits of wood upon a quiet surface of *clean* water. The dish of water used for this purpose should be at least 6 or 8 inches in diameter. Care should be used not to allow the two sticks to approach too near the edges of the vessel. You will be interested in observing what happens when the floating stick does come near the edge of the vessel. Now take a small cake of soap, or a small bit of soap on the point of a penknife, and touch it to the surface of the water between the two floating sticks. What is the effect upon the sticks? How do you explain this motion? If we consider the surface of the clean water as pulling the sticks apart, and the soapy surface as pulling them together, which of these two surfaces is the stronger?

Exercise 36. — Measurement of Surface Tension

Reference. — CREW, 127.

Apparatus. — Hydrostatic balance with telescoped upright. A Jolly balance, preferably the Linebarger form, may be used if available. Set of weights; three or more fork-shaped pieces of wire, with parallel prongs, as in Fig. 49; No. 20 aluminium wire is suitable for this purpose; the widths of different forks, between prongs, should vary from 3 cm. to 6 cm. or more; the prongs themselves may be about 4 cm. long in all the forks; a strong solution of "Ivory" or Castile soap in water; crystallizing dish, or wide beaker; millimetre scale.

Problem. — To measure the force exerted by the two surfaces of a thin film of liquid, and hence to find the surface tension of the liquid of which the film is composed.

Experiment. — (*a*) Suspend a wire fork from one of the balance pans by means of a piece of wire bent into a hook at each end. (See Fig. 49.) Allow the prongs to dip into the soap solution. Adjust the height of the balance beam, or the length of the supporting wire, so that when the beam is in equilibrium the horizontal cross-piece of the fork is one or two centimetres above the liquid. Find the weight necessary to balance the fork in this position. (If a Jolly balance is used, it will be necessary to find also the value of one scale division in grammes' weight.)

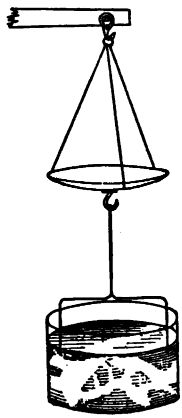

FIG. 49. — Measurement of the force with which a pair of liquid surfaces tend to contract.

(*b*) The fork is now to be completely immersed for a moment, and then brought back to its former position. The area enclosed between the fork and the liquid surface will now be occupied by a soap film. By virtue of its surface tension, this film will exert a downward pull on the fork. Find the weight now required to produce equilibrium.

(*c*) From the above results, determine the amount of vertical pull due to the tension of the two surfaces of the film. One-half of this will be the vertical force exerted by a single surface. Express this force in dynes. (If a Jolly balance is used, it will be necessary to express the difference between the reading of (*a*) and that of (*b*) in dynes.)

(*d*) Remove the fork from the solution, being careful not to bend it in the least. Find the width of the film by measuring the distance between the prongs of the fork, at the points where the prongs intersected the surface of the liquid when the balance was in equilibrium. These points need not be accurately determined if the prongs are nearly parallel; estimate their position as well as you can.

(*e*) You have already obtained, in (*c*), the force exerted by one surface of the film, and have expressed this force in dynes. Now divide this force by the width of the film expressed in centimetres, and so find the force which the surface exerts per unit width. This quantity is called the **surface tension** of the liquid in question.

(*f*) Determine the surface tension for this solution by using in turn each of the remaining forks. Record your results in tabular form, under the following heads: "Mass balancing fork and film"; "Mass balancing fork alone"; "Force due to film, in dynes"; "Force due to one surface of film"; "Width of film"; "Surface tension."

(*g*) How many ergs of work would be done against surface tension, if a fork 5 cm. wide, dipping into your solution, were lifted through a height of 2 cm.? How much energy will be thus stored up *in each square centimetre* of the surface of film? Compare this result with the value of the surface tension. Would it, in your judgment, be allowable to define surface tension as energy per unit area of surface?

Why are raindrops spherical in form? Why does a small stream of water flowing from a tap ordinarily break up into drops?

SECTION 3. — PROPERTIES OF GASES

Exercise 37. — Boyle's Law *

References. — Crew, 136–140; Rowland and Ames, 78; Carhart and Chute, 153–154; Wentworth and Hill, 79; Gage, 108; Avery, 169.

Apparatus. — Wide-mouthed bottle having a capacity of about 4 ounces; three-holed rubber stopper to fit the bottle tightly; three pieces of glass tubing, $\frac{1}{4}$ inch inside diameter — one about 90 cm. in length, open at both ends; the other about 80 cm. long, with one end sealed off square; and a third piece, 7 or 8 cm. long, bent in the middle at right angles; two feet of ordinary rubber "pressure tubing"; bicycle hand pump; two Hoffmann pinch-cocks; metre stick; 3-inch steel try-square; mercury.

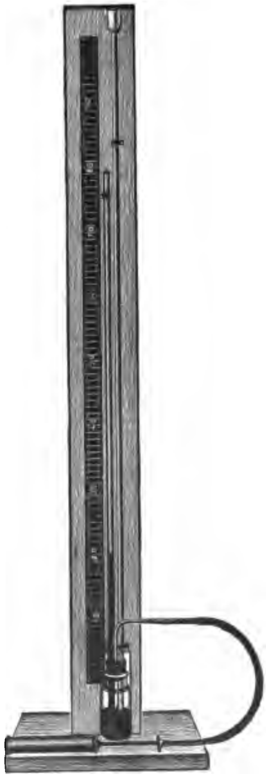

Fig. 50. — A convenient apparatus for verifying Boyle's Law in the case of pressures ranging between one-half and two atmospheres.

Pass the three glass tubes through the rubber stopper. The projecting ends of the longer tubes should reach to the bottom of the bottle. (See Fig. 50.) Fill the bottle about half full of mercury. Pour some mercury into the closed tube, and invert it into the bottle. Perhaps the easiest way of doing this is to fit a small cork lightly into the open end of the tube before inverting it. After inversion, this cork can be driven out by

* The following form of this experiment was first seen by one of the authors in the Ryerson Laboratory of the University of Chicago, in 1894.

lightly jolting the mercury. Make the surface of the mercury in this tube stand 2 or 3 cm. above the top of the cork, admitting more air if necessary. Fit the cork to the bottle, and tie or wire it in securely. All the connections must be thoroughly air-tight. Put two strong screw pinch-cocks on the rubber tube and attach one end to the short glass nozzle, and the other end to the bicycle pump. It is advisable to fit a short piece of wide glass tubing to the top of the open tube, by means of a cork bushing, to prevent the spilling of mercury. Mount the apparatus upon an upright board, as in the figure. Screw the metre stick to this board, parallel to the tubes, and as close to them as convenient. (See Fig. 51.)

Problem. — To find how the volume of an enclosed portion of air varies with the pressure which it exerts, or which is exerted upon it; in other words, to test the truth of Boyle's Law, which states that the volume of a given mass of gas varies in inverse proportion to its pressure, when the temperature is constant.

Experiment. — The portion of air to be experimented on is that contained in the closed glass tube, and separated from the air of the room by the mercury column in the tube. The pressure upon this specimen of air may be increased by working the pump, thus increasing the pressure within the bottle, and forcing mercury upward into both tubes. When desired, the pressure may be retained and the columns kept at a fixed height, by closing the pinch-cock.

(*a*) Read from a barometer the pressure of the air in the room, expressed in centimetres of mercury.

(*b*) Work the pump until the mercury stands at the same height in both tubes. What is now the pressure on the enclosed air, in centimetres of mercury? Raise the mercury in the open tube 1 cm. above that in the closed tube. What is now the pressure of the enclosed air? If the level of mercury in the open tube is placed 1 cm. *below* that in the closed tube, what pressure is exerted upon the enclosed air? Does the *volume* of the enclosed air become greater, or less, when its pressure is increased?

It is here assumed that the temperature does not change. This is never strictly true. If the enclosed air grows warmer, how will this affect the volume, other things being the same? How will increase of temperature affect the *pressure*, other things being the same?

It should now be clear that the upright tubes, together with the bottle into which they dip, form a **manometer**, that is, an apparatus which will serve to measure the pressure of the enclosed air, in centimetres of mercury, provided the reading of the barometer be also taken into account.

For the *volume* of the enclosed air we need only measure the *length* of that portion of the uniform tube which the air occupies. For, doubling the length of the air-column evidently doubles its volume. Since, then, the volume of a tube of uniform cross-section is proportional to its length, we shall represent the volume of air by the number of centimetres in the length of the air-column.

(*c*) Pump the mercury in the open tube to a point near the top. To obtain the pressure and volume of the enclosed air, read the positions on the metre stick of the following three points: *A*, surface of mercury in the open tube; *B*, surface of mercury in the closed tube; *C*, top of the air-column, *i.e.* top of closed tube. The readings may be accurately made by holding a try-square in the position shown in Fig. 51. By letting out a little air at a time, using one pinch-cock as a regulator, make about ten sets of readings of the positions of the two mercury surfaces.

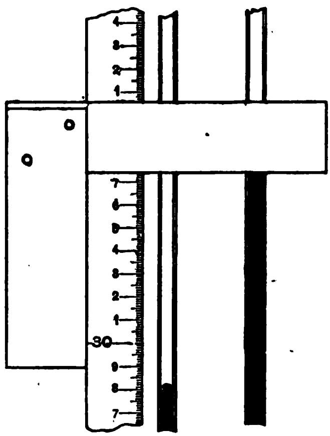

Fig. 51. — Method of measuring height of mercury column.

(*d*) In terms of *A*, *B*, and *C*, what represents the pressure of

the enclosed air, due to the mercury in the apparatus? What represents the *total* pressure of the enclosed air? What represents its volume?

Record your readings, and also the quantities computed from them, in tabular form. In the last column, enter the products obtained by multiplying the pressure of the enclosed air, at any time, by its corresponding volume. Is this product approximately a constant? What may be said of two quantities which vary in such a way that their product remains constant? Do your observations indicate that Boyle's Law is true for air?

(*e*) Plot a curve, taking the pressures of the enclosed air as abscissas, and the corresponding volumes as ordinates.

Exercise 38. — The Absorption of Gases

References. — Carhart and Chute, 36; Avery, 49; Wentworth and Hill, 137.

Apparatus. — Three small test-tubes; a small dish, or pan, of water 5 or 6 inches deep; 3 or 4 cc. of stronger ammonia; 1 or 2 square inches of platinum foil; a pair of pincers; a Bunsen flame.

Problem. — To illustrate the absorption and occlusion of gases.

Experiment. — (*a*) Take about 1 cubic centimetre of "stronger ammonia" in a small test-tube. Place your thumb over the top of the tube and heat the ammonia gently. Ammonia gas is driven off, and this gas expels a large portion of the air from the tube. You can feel this gas escaping past your thumb. As soon as this occurs, *without removing your thumb*, quickly invert the test-tube over the vessel of water. Do not remove your thumb until the mouth of the test-tube is under water.

When you immerse the test-tube in water *immediately* note about how much gas there is in the tube when the level of the water is the same inside and outside the tube. How does the

volume of this gas change as time goes on? What becomes of the gas in the tube?

(*b*) Repeat the same experiment, using water instead of ammonia. Apply about the same amount of heat as before. Report your result. Explain the difference.

(*c*) Roll up a small piece of platinum foil into a cylinder, in the same manner that carpet is rolled up. Holding this by a pair of pincers, heat it to a bright redness in a Bunsen flame. Now pinch the rubber tube which supplies the gas until you extinguish the flame. After about one second insert the platinum into the jet of escaping gas. What happens to the platinum? Remove the platinum again for a second or so until it has ceased to show bright red. Again insert it into the escaping coal gas. What happens? How do you explain this?

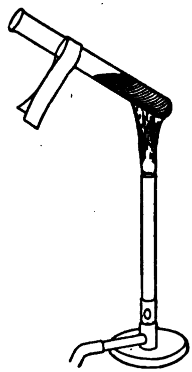

Fig. 52.—To expel the dissolved air from water by heating.

(*d*) Take two small test-tubes and fill each with water freshly drawn from the tap. Set one of them aside, and let it remain quiet for five or ten minutes. In the meantime hold the other test-tube over a flame, by means of a folded paper, as indicated in Fig. 52, until the water in it is brought to active boiling. Now set this tube away beside the other, and at the end of 10 minutes note the difference in the two tubes. How do you explain this difference? Why does soda water effervesce so violently when freshly drawn from the fountain?

CHAPTER IV

WAVE MOTION

Exercise 39. — Waves in the Surface of Water

References. — Crew, 146–150; Rowland and Ames, 67; Carhart and Chute, 403.

Apparatus. — A wave trough: this is simply a long water-tight box of which one side is of plate-glass. The following dimensions will be found convenient, viz., length, approximately 6 feet; width, 3 to 4 inches; depth, 5 to 6 inches. The exact length and depth may well be determined by the dimensions of the strip of plate-glass which is available. All the sides except the glass one should be made of 1½ inch stuff;

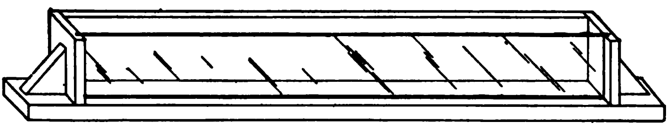

Fig. 53. — **Wave trough devised by the Weber brothers.**

seams stopped with white lead and putty. Such a trough is shown in Fig. 53. A clock or watch. A stop-watch is very convenient, but not essential to good work. A thin wooden paddle whose blade is not quite as wide as the trough; block of wood with upright rod for handle; metre stick.

Problem. — To study waves in shallow water; and to determine how the speed of the wave depends upon the depth of the water. Indeed, this experiment is intended to illustrate the fact that, in general, the speed of any kind of waves depends upon the medium in which these waves travel.

Experiment. — (*a*) Fill the trough with water to the depth of about one inch. Start a wave by quickly heaping the water up at one end of the trough. A large single wave of this kind can be started either by slightly lifting one end of the trough, or by using a broad wooden paddle. Take the paddle in one hand, place it vertically about a foot from one end of the trough, and you can then produce a large wave by drawing the paddle rather quickly to the near end of the trough.

This wave will "run" to and fro along the trough many times, being reflected first at one end and then at the other. If you observe the rise and fall of the water at one end of the trough, you will be surprised to see how many round trips of such a wave can be detected.

(*b*) Now measure with your watch the time occupied in six round trips of the wave, by noting the sudden rise and fall at one end of the trough. Do not try to follow the wave *along* the trough while making observations, but concentrate your attention at one end. Measure also the inside length of the trough, and compute the speed at which the wave travels in this depth of water. Measure and record the depth of water.

(*c*) Repeat this experiment after you have poured into the trough water sufficient to increase the depth by 2 cm. In this manner measure the speed of the wave at six different depths. Record your results in a table similar to the following:

Length of trough = cm.

Obs.	Depth of water in cm.	No. of round trips	Time in sec.	Computed speed in cm. per sec.
1				
2				
3				
4				
5				
6				

(*d*) *Stationary* (*or standing*) *waves.* —

To produce stationary waves, lay a block of wood (with an upright for handle) on the water very near one end of the trough. By raising and lowering this block at a uniform and rather rapid rate the best results are attained. A "train" of running waves will be thus produced, continually moving *away from* the paddle; this train, after being reflected at the far end, will move back toward the paddle. These two trains "interfere" to produce a series of waves which lose all appearance of motion, except in a vertical direction; hence the name *stationary* waves. A little practice will enable you to produce this phenomenon in the most beautiful manner, so that the whole trough appears to be filled with waves which are simply "see-sawing."

This method of studying water-waves was first employed by the Weber brothers, two Germans, who investigated this subject about 1825.

Exercise 40. — Transverse Waves in Stretched Strings

References. — Crew, 163–168; Rowland and Ames, 90; Carhart and Chute, 451; Avery, 209–210.

Apparatus. — An electrically driven tuning-fork; the pitch of this fork may well lie somewhere between 30 and 60. Three pieces of wrapping thread such as grocers use for tying up packages. These three strings should be of different "weight," that is, of different linear density, say light, medium, and heavy. A small pulley which can be clamped to the table so as to stand at the same height as the tuning-fork. A long table, or two short tables, which may be placed together so as to give a length of 8 or 10 feet; small scale pan; set of weights; metre stick; battery to drive tuning-fork.

Problem. — A study of transverse waves and of stationary vibrations; a study also of the manner in which the speed of waves depends upon the medium; being an introduction to the study of forced vibrations and sound-waves.

Experiment. — Arrange your apparatus on a long table as indicated in Fig. 54.

(*a*) It is proposed, first of all, to measure the speed with which a wave travels in a string. When you set the tuning-

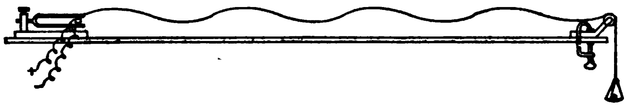

FIG. 54. — Melde's method of studying transverse waves in stretched strings.

fork going it acts exactly as one's hand does in starting up waves in a clothes line or rope, only the tuning-fork does this with much greater regularity and rapidity than the human hand can do it. The string is evidently forced to vibrate; not only so, but it is forced to vibrate at the same rate as the fork. Hence the name "forced vibrations."

After you have put a small weight in the scale pan to stretch the string, and have set the fork in vibration, try increasing or diminishing the distance between the fork and the pulley. You will find that in this way you can increase the vibration, while certain points in the string appear to stand very nearly still. What are these points called? How do you explain the fact that these points remain at rest while all the rest of the cord is in vibration? Measure the average distance between two consecutive nodes; call this distance L. How do you explain the fact that a wave-length is *twice* the distance between two consecutive nodes?

Call the frequency of the fork N. Ask your instructor for the numerical value of N. If we call the speed of the wave V, and its length l, we know, from the fundamental equation of wave-motion, that

$$V = Nl = 2\,NL.$$

(*b*) Now increase the weight in the pan, that is, increase the stretching force on the string. This does not appreciably affect the frequency of the fork. What change do you observe in the

length of the vibrating segment? What effect, therefore, does the increase of stretching force have upon the speed of the wave?

(*c*) Now exchange the string which you have been using for a heavier or lighter one, but let the stretching weight remain exactly the same as before. Note that the frequency of the fork is not appreciably changed by putting on another string. Do you find the length of the vibrating segment the same in the light as in the heavy string? How, therefore, is the speed changed when the heavy string is put on?

(*d*) What makes the vibrations of the string die out so quickly when the tuning-fork stops? Is the energy of the vibrating string kinetic or potential, or is it partly kinetic and partly potential? How do you explain the fact that in any of the above experiments the amplitude of the vibration depends upon the distance between the fork and the pulley? Why must this distance be a whole number of half wave-lengths if the amplitude is to be large?

CHAPTER V

SOUND

MEASUREMENT OF THE SPEED OF SOUND IN SOLIDS

In order to compare the speed of sound in a solid with the speed in air, the apparatus indicated in Fig. 55 will be found excellently adapted.

The rod, *AB*, is made of brass, glass, or other substance in which you wish to know the speed of sound. The end *B* carries a disk of cork which fits loosely into the glass tube, *BD*. The middle point of *AB* is tightly clamped in a vise. At the other end of the tube is a second disk, *D*, which may be moved lengthwise of the tube, so that the length of the column of air between *B* and *D* may be changed at will. A little cork dust is placed in the tube, and distributed evenly along the bottom.

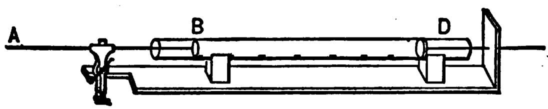

Fig. 55. — Kundt's device for studying sound-waves.

If the free end of the rod be rubbed with a rosined cloth (or simply a wet cloth if a *glass* rod is used), the entire rod will be set into longitudinal vibrations, becoming alternately longer and shorter than its undisturbed length. At each elongation of the rod, the cork disk starts a compression in the air-column, and this is quickly followed by a rarefaction as the rod shortens. The vibrating disk thus sets up a train of waves, which travels to the other end of the tube, and is there reflected. If the air-column be made of the proper length,

stationary waves will be formed in the air-column, the presence of nodes and loops being clearly shown by the dust, which remains undisturbed at each node, but is violently agitated throughout the segments lying between them. Since each elongation of the rod starts a new compression down the tube, the frequency of the air vibration must necessarily be the same as the frequency of the rod. In other words, the motion of the air-column is a *forced vibration*.

We may now make use of the following equation, which gives the speed of *any* wave-motion, viz.,

$$V = Nl,$$

in which V is the speed, N the frequency, and l the wave-length. So that if N_1 and l_1 represent the frequency and the wave-length, respectively, of the disturbance in the rod, and N_2 and l_2 the frequency and wave-length in air, we may write the ratio of the speeds,

$$\frac{\text{Speed in the rod}}{\text{Speed in air}} = \frac{N_1 l_1}{N_2 l_2}.$$

But whenever stationary waves are formed, the wave-length is twice the distance between consecutive nodes, or what is the same thing, between consecutive antinodes. Hence if we let L_1 represent the length of the rod, we shall have

$$l_1 = 2\,L_1.$$

Also, if L_2 be the distance between consecutive dust heaps in the air-column,

$$l_2 = 2\,L_2.$$

Hence the above equation becomes

$$\frac{\text{Speed in the rod}}{\text{Speed in air}} = \frac{N_1 l_1}{N_2 l_2} = \frac{2\,N_1 L_1}{2\,N_2 L_2} = \frac{L_1}{L_2}$$

for since the frequencies are the same, $N_1 = N_2$.

Thus we see that in order to find the ratio of the speed of sound in the material of which the rod is made to the speed

of sound in air, we have merely to find the ratio between the length of the rod and the average distance between dust heaps in the air-column.

This method of studying waves was devised by Kundt, late Professor of Physics in the University of Berlin.

Exercise 41. — Speed of Sound in Brass — Kundt's Tube

References. — Crew, 185, 193; Avery, 211–213; Rowland and Ames, 92–93.

Apparatus. — Kundt's tube, as in Fig. 55; this instrument is now supplied in a cheap and efficient form, and should be found in every laboratory of physics. An excellent form is that employed in the Harvard Laboratory, and made by Gleeson, 106 Sudbury Street, Boston. Metre stick; small piece of cotton or woollen cloth; powdered rosin.

Problem. — To compare the speed of sound in brass with that in air. A study of forced vibrations.

Experiment. — (*a*) See that the rod is clamped at its *middle* point. By shaking the apparatus, or in some other way, distribute the cork dust evenly along the tube from one cork disk to the other. Now produce a clear musical note by rubbing the rod with the cloth, on which a little powdered rosin has been sprinkled. A light, steady grasp will be found most effective.

After rubbing once or twice, adjust the movable disk, moving it a very short distance, say 2 or 3 mm. Continue to excite the rod, and adjust the length of the air-column alternately, moving the disk always in the same direction, until the dust begins to be agitated. After this, only a slight further adjustment will be needed to produce fairly sharp nodes. The final adjustment is most easily made by rotating the tube a little on its supports, so that the dust is carried up to one side. On exciting the rod, the dust lying in the disturbed regions between the nodes will slide down, while the nodes themselves

will be marked by fairly sharp peaks of dust projecting up the side of the tube.

(*b*) With a metre stick, determine the length of the brass rod, and hence compute the wave-length of the vibration in the rod.

(*c*) Find the distance between the successive nodes in the air-column. Do not measure single segments, but select two nodes as far apart as possible, and measure the distance between these. Divide this distance by the number of intervening segments, and so obtain the length of one segment.

(*d*) Repeat the above, by finding a *new position* of the movable disk which will give you stationary waves. Make, altogether, four or five separate determinations of the length of a segment in the air-column.

(*e*) Does sound travel more rapidly in air or in brass? What do you find to be the ratio of the speeds? Taking the speed of sound in air at the ordinary room-temperature to be 345 metres per second, compute the speed in brass.

Record your observations in tabular form.

Exercise 42. — The Phenomena of Resonance

References. — Crew, 173–174; Rowland and Ames, 84; Gage, 187–191; Avery, 205; Carhart and Chute, 425–428; Hall and Bergen, 364–365; Wentworth and Hill, 351–352.

Apparatus. — An iron or lead ball, weighing between one and two pounds; a small tuning-fork, whose pitch is somewhere between middle C and its upper octave; a jar of water — such a jar as is used for Nicholson's hydrometer will serve well; a glass tube, more than an inch in diameter, yet not too wide to go into the jar just mentioned; an iron stand with clamp to hold this tube; a small piece of sole-leather, say 10 or 12 square inches; a metre stick.

Problem. — To illustrate the manner in which energy may be accumulated in a vibrating body; to show, also, the transfer

of energy from one body to another by means of a wave-motion in an elastic medium.

Experiment. — (*a*) Suspend a heavy ball from a stand or wall-bracket, as indicated in Fig. 56. Let the suspension string be about 3 feet long. It will form, therefore, an ordinary gravitation pendulum. Now give the ball a very slight tap with a lead pencil held gently in one hand. Observe carefully in which direction the ball is vibrating, and again give it a slight tap when it passes through its position of equilibrium going to the left. At first you will notice very little change in the motion of the ball, but keep on giving the ball a slight tap every time it passes through its position of equilibrium *going to the left.* What is the effect of 15 or 20 taps of this kind? Where does the ball get the energy it has acquired?

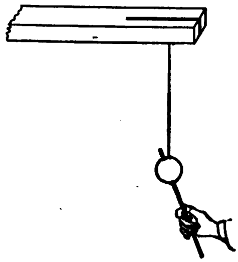

Fig. 56. — A simple case of resonance.

(*b*) Now bring the ball to complete rest, and again give it 15 or 20 taps such as you gave it before, only now distribute the taps in the most irregular manner, making the blows now rapid, now slow. What is the effect upon the iron ball? What becomes of the energy of these 15 or 20 blows? How do you explain the vast difference between this case and the one discussed under paragraph (*a*) above?

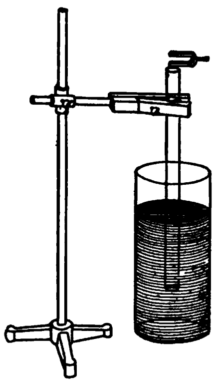

Fig. 57. — An air-column which can be adjusted in length so that its period is equal to that of a given tuning-fork.

(*c*) A tuning-fork is an instrument capable of giving very regular blows to all the air which surrounds it. Furthermore, a column of air of definite length is a body which has a definite period of vibration, just as the pendulum which we have examined.

You can test this for yourself by the following experiment. Arrange a jar of water, with a glass tube dipping into it, as indicated in Fig. 57. Set a tuning-fork into vibration by striking one prong on a piece of sole-leather. Hold the ends of the prong above the tube, and observe that by changing the length of the air-column you can reach a point where the air-column will begin to "sound," that is, the air-column is itself set into vibration by means of the fork. This is the phenomenon of **resonance**. Measure the length of the air-column when this resonance is a maximum. Call this length L. The air-column is a vibrating body with a node at the surface of the water and a loop (or antinode) almost exactly at the top of the tube. The length of the air-column is, therefore, practically one quarter of the length of the wave which it emits.*

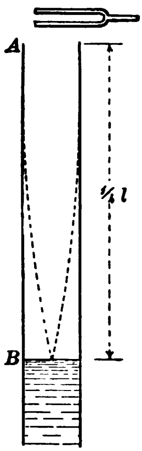

FIG. 57 *bis*.

The frequency of the fork is generally marked on it. Call this N. Then, if V be the speed of sound in air, and l the wave-length,

$$V = Nl = 4\,NL.$$

From your observations you can, therefore, compute the speed of sound in air. Make ten different measures of L and use the average value.

Exercise 43. — Transverse Waves in Stretched Strings

(*Variation of length with stretching force in a string of constant pitch.*)

References. — CREW, 165, 172; ROWLAND AND AMES, 90; CARHART AND CHUTE, 451; HALL AND BERGEN, 371; AVERY, 209–210.

* The fact that the antinode is not exactly at the top of the tube, but falls a little above it, is due to the inertia of the air just outside the mouth of the tube. The details of this explanation are somewhat complicated, but may be found in Lord Rayleigh's *Scientific Papers*, Vol. I, pp. 33–76.

Apparatus. — Sonometer; tuning-fork, whose pitch lies somewhere between 200 and 300; strip of sole-leather; set of weights, ranging from 500 g. to 4 kg.; 5 or 6 feet of steel piano wire, having a diameter between 0.3 and 0.6 mm.; metre stick.

Problem. — This experiment is intended to answer the following question: When the tension on a string varies, how must one alter the length of the string in order to keep the pitch of the string constant?

Experiment. — (*a*) Stretch a steel piano wire over a sounding-box as indicated in Fig. 58. Having fixed one end of this wire

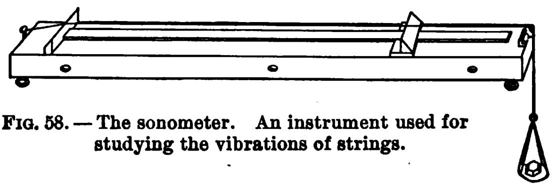

Fig. 58. — **The sonometer. An instrument used for studying the vibrations of strings.**

to a binding-post on the sounding-box, attach to the other end a scale pan in which you can place various loads ranging from 1 to 4 kg. At this end of the box the wire is to be strung over a rotating arm or pulley as shown in figure.

In addition to this the wire is to be supported on two little "bridges," one of which is movable and can slide along the box, so that the length of the vibrating segment can be varied at will. Such an arrangement is called a **sonometer.** If you pluck this stretched wire with your finger, will the vibrations of the wire be "free" or "forced"?

(*b*) Having put your apparatus into working order, begin with a stretching weight of 1 kg. Strike your tuning-fork on a piece of sole-leather and hold the stem of the fork against the box of the sonometer to reënforce the sound. You can reproduce this same note by plucking the string and moving the sliding bridge one way or the other. Perhaps the easiest way to tell when you have a length of wire which will give the same

note as the fork, is, to fold a small strip of tissue paper into the shape of an inverted V, thus, Λ, and put it astraddle the wire. This little paper is called a "rider."

When the movable bridge reaches the right place, resonance will occur between the fork and the wire so that you can throw the rider off the wire by merely sounding the tuning-fork and holding its stem against the box of the sonometer. If your ear is reasonably accurate, you may not need the aid of a rider. Having obtained unison, measure and record the length of the vibrating segment of the wire.

(c) Now use a stretching weight of 2 kg., then of 2½, 3, 3½, and 4 kg. in succession; determine for each of these the length of wire which will give the same note as that of the tuning-fork.

Record your observations in a neat form under the headings, "Stretching Weight" and "Length of Vibrating Segment."

Exercise 44. — Transverse Waves in Stretched Strings

(Variation of pitch with length in a string under constant tension.)

References. — Crew, 165, 172; Rowland and Ames, 90; Carhart and Chute, 451; Hall and Bergen, 371; Avery, 209–210.

Apparatus. — Sonometer, with cloth scale pan, and a steel piano wire, 0.3 to 0.6 mm. in diameter; weights amounting to about 4 kg.; set of four tuning-forks of different and known frequencies, such as *C*, *E*, *G*, and the octave of *C*; piece of sole-leather.

Problem. — To find how a change in the length of a vibrating wire affects its frequency, when the stretching force is kept constant.

Experiment. — (*a*) Pass the sonometer wire over the bent lever (or pulley) at one end of the sounding-box, and attach the scale pan. We have now an apparatus in which the length of the vibrating wire may be altered at will, without changing the stretching force. This is done by sliding the movable

bridge along the box, keeping the wire in contact with it. Put enough weight in the pan to straighten the wire, and cause it to give out a clear note when plucked. From 3 to 4 kg. should answer well.

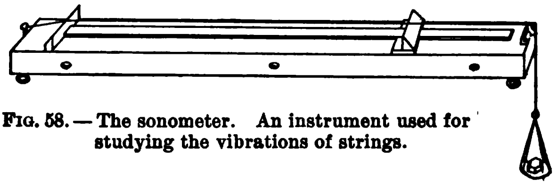

FIG. 58. — The sonometer. An instrument used for studying the vibrations of strings.

In order to find the pitch of the wire at any time, we shall adopt the plan of making this the same as some known pitch, namely, that of a tuning-fork. Sound one of the forks by striking it on the leather, and touch its stem to some part of the sounding-box. If the wire happens to be in unison with the fork, the wire will be set in vibration by resonance. If not, slide the bridge in one direction or the other, until the wire and the fork are in unison. To detect the vibration of the wire, hang upon it one or more narrow strips of tissue paper bent into the form of a V. These are commonly called "riders."

(*b*) Measure the length of wire which has been found to have the same frequency as the fork used. Make two or three more trials, and take their mean.

(*c*) Find, as above, the mean length of wire which is in unison with each of the remaining forks. Record your observations in tabular form, under the headings: "Frequency (N)"; "Length of Wire (L)" — three trials and mean; and finally "$N \times L$."

(*d*) Judging from the column in the table headed $N \times L$, how does the pitch vary with the length of the wire, for constant stretching force?

(*e*) Plot a curve, with lengths as abscissas, and frequencies as ordinates.

Exercise 45. — Pitch of Tuning-fork

References. — Crew, 167, 199, 204; Carhart and Chute, 451; Avery, 210; Hall and Bergen, 371.

Apparatus. — A standard tuning-fork, *i.e.* one whose pitch is known; a second fork of unknown pitch; sonometer; metre stick; piece of sole-leather; about 4 kg. of iron weights.

Problem. — Having given two tuning-forks, to find the pitch of one, when the pitch of the other is known. The method is to find the lengths of wire which are in unison with the two forks respectively.

Experiment. — (*a*) Make the tension of the sonometer wire such that the pitch of the wire without the movable bridge is lower than that of either fork. Then, by means of the movable bridge, find the length of wire which is in unison with each of the forks. This may be done by using tissue paper riders, as explained in the preceding exercises. It is a well-known fact that the frequency of a given wire is inversely proportional to its length, when the tension is constant, as illustrated in Exercise 44. Hence, if N_1 and N_2 represent the frequencies of the standard fork and the other fork respectively, and L_1 and L_2 the corresponding lengths of the vibrating wire, we have the equation

$$\frac{N_2}{N_1}=\frac{L_1}{L_2},$$

from which, having measured L_1 and L_2, and having N_1 given, we may find N_2, the pitch of the unknown fork.

(*b*) Make two more determinations of the pitch of this fork, changing the tension each time by a half kilogram. Record your results in tabular form.

Exercise 46. — Interference of Sound Waves

References. — Crew, 170–171; Avery, 206; Wentworth and Hill, 353; Gage, 190; Carhart and Chute, 433–434.

Apparatus. — A tuning-fork, preferably with a pitch lying

between 200 and 300; a jar of water, tall enough to show resonance with this fork; piece of sole-leather; a paper cylinder to slip over one prong of the fork.

Problem. — To study the effect of two trains of sound-waves when added together.

Experiment. — (*a*) As you stand and hold a vibrating tuning-fork directly in front of you, with the two prongs *A* and *B* in the straight line joining the fork and your ear, the prongs will alternately approach and recede from you. (See Fig. 59.) You know this to be the fact, even though you cannot see the prongs move; for whenever a fork vibrates its prongs alternately approach and recede from *each other*. The consequence is that when the prong *A* is producing a condensation in the air, the other prong, *B*, is moving away from you, and, therefore, producing a rarefaction on the side toward you. Each prong is sending a train of waves to your ear. If you stand in the line *AB*, the condensation from *A* will reach your ear a little earlier than the rarefaction from *B*. But, by turning the fork slightly around its stem as an axis, the prong *B* will be brought a little nearer your ear and prong *A* will be carried a little farther away from your ear. You might, therefore, expect to reach a point where the rarefaction from *B* and the condensation from *A* would reach your ear at the same instant. And if so, one of these ought nearly to undo the effect of the other, thus producing silence. Hold the fork rather close to your ear, and see whether you can find a position of the fork where it suddenly becomes silent, or nearly so, and where on rotating it slightly farther, you again hear it. Can you detect more than one of these positions? How many?

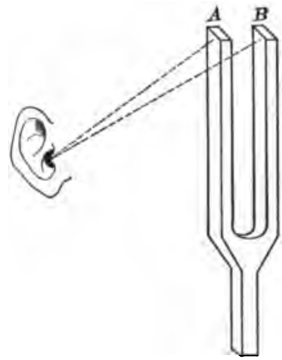

Fig. 59. — Illustrating the two trains of waves which reach the ear from a tuning-fork.

(*b*) We now wish to test the correctness of the explanation which has just been given. For this purpose take a sounding-box or a jar of water such that the air column over it will "resonate" to the fork. You can readily adjust the water to the proper depth. Set the fork into vibration and hold it over the jar as indicated in Fig. 60. Now rotate the fork about its stem as an axis, until no resonance is heard, that is, until the wave trains from the two prongs "interfere." While the fork is in this position and still vibrating, carefully slip a little paper cylinder over one prong. This will prevent the disturbance from that prong entering the jar. If, now, the silence of the fork is really due to the fact that we have added two sounds together to produce silence, then, on taking away one source of sound the other ought to remain. Try this and see whether, on slipping the cylinder over *one* prong *without touching it*, the sound reappears. The paper cylinder should be passed well over the prong, not merely over the tip end of it. This experiment is not difficult, but it demands careful manipulation.

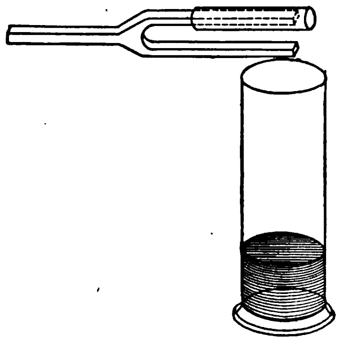

FIG. 60. — Illustrating the fact that two trains of waves are necessary to produce interference.

The question to be determined is whether you can add two sounds together and thus produce silence; and later cover up one of these sounds, so to speak, and thus make the remaining one audible.

Exercise 47. — The Phenomenon of Beats

References. — CREW, 207–208; ROWLAND AND AMES, 87; WENTWORTH AND HILL, 354; CARHART AND CHUTE, 435–436; AVERY, 207.

Apparatus. — Two tuning-forks of nearly equal pitch; a small bit of soft wax; a few square inches of sole-leather; watch or clock.

Problem. — To observe the phenomenon of beats, to explain their production, and to employ the phenomenon to measure the difference in frequency between two vibrating bodies.

Experiment. — (*a*) Two vibrating tuning-forks held in front of you will each send a train of waves to your ear. If the two forks have exactly the same frequency they will vibrate in perfect unison and the effect upon the ear will be perfectly uniform. If, however, one fork vibrates a little more rapidly or a little more slowly than the other, it will keep on gaining or losing until, by and by, the forks will differ in phase by one *whole* vibration. The effect upon the ear will then be the *sum* of the effects of the two trains. But a little later, the forks will differ in phase by half a vibration, and the effect upon the ear is now the *difference* of the effects of the two trains.

In case the two forks differ in pitch we may, therefore, expect an alternate rise and fall of sound. Try the forks which you have and see whether you can detect such a rise and fall when both forks are sounded together. Where else have you heard this same phenomenon? This waxing and waning of sound is the phenomenon known as **beats**. Count and record, unless they are too rapid, the number of beats which you hear in 15 seconds.

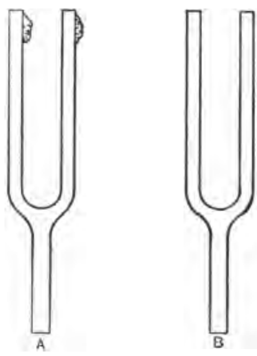

FIG. 61. — The pitch of a tuning-fork is lowered by loading with wax.

(*b*) Now place a small piece of soft wax on each of the prongs of *one* fork, as indicated in Fig. 61, and again observe the beats by setting both forks into vibration. In general, the beats will be more rapid or less rapid than before. To be definite, let us suppose that the beats are more rapid than before; have you, therefore, increased or diminished

the *difference* in pitch between the forks? The wax increases the inertia of the fork, but does not change its elasticity. The wax must, therefore, always slow up the fork to which it is attached. Suppose then that you increase the difference of pitch between two forks *A* and *B*, by slowing up *A*, which fork had the higher pitch, *A* or *B*? Unless you have put too much wax on *A*, it is highly probable that *A* has the lower pitch.

(*c*) You can test this by removing the wax from *A* and putting it on *B*. The wax will slow up *B*, so that if now *A* really has the lower pitch, the forks will be brought more nearly into unison; and, accordingly, the beats will be slower.

By counting the rate at which the forks beat when neither one is loaded with wax, you can determine how much they differ in pitch, but you cannot say which has the higher pitch. By loading the forks alternately with wax you can determine which of the forks has the higher pitch. Do this for the forks which you have and report upon them. Try the effect of putting wax on one prong, then of doubling the amount of wax, then of trebling it. What effect upon the rate of beating?

CHAPTER VI

HEAT

INTRODUCTORY

We pass now to a form of energy which is rather more difficult to study than any of those forms which we have hitherto considered. One reason for this is that heat cannot be detected by either the sense of sight or the sense of hearing. Another reason is that we do not know any body which will "hold heat." Heat is continually leaking out of a hot body and continually flowing into a cold body. The consequence is that quantities of heat are very difficult to measure with any degree of accuracy.

It will be seen, however, from the following exercises that, in spite of these difficulties, differences of temperature can be measured with great precision, and that thermometry is a fairly accurate science.

The aim of these exercises is to make clear the principles upon which thermometers are constructed, and the principles which govern the transfer of heat from one body to another. The student who follows the exercises here involved will also acquire considerable insight into the nature of heat.

SECTION 1.—MEASUREMENT OF TEMPERATURE

Exercise 48. — Change of Volume with Temperature

References. — Crew, 234, 236, 240; Rowland and Ames, 105; Hall and Bergen, 288; Wentworth and Hill, 91–93; Carhart and Chute, 206–208; Avery, 230–232.

Apparatus.—A glass bulb somewhere between 1 and 2 inches in diameter, provided with a stem having a small bore, say, between 1 and 2 mm.; some six or eight inches of rather thin-walled glass tubing, having a diameter between 8 and 12 mm.; a flask provided with a two-hole cork to receive the stem of the bulb mentioned above; wooden clamp; Bunsen burner.

Problem.—To illustrate the change of volume which solids, liquids, and gases undergo when heated.

Experiment.—(*a*) Fit a flask of water with a cork which has two holes in it. Through one of these holes pass the stem of a glass bulb, so that the end of the stem is immersed under water, as shown in Fig. 62. By slightly heating the bulb, either by a lighted match or by passing a flame over it for an instant, you can drive a little of the air out, so that when the bulb cools to the temperature of the room the water will rise to about the point *A* in the stem, as indicated in Fig. 62. If this is not the case, drive out a little more air or remove the bulb for a moment and let in a little more air, whichever is required to make the water stand at the proper height.

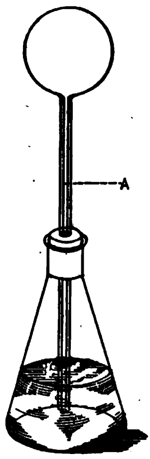

FIG. 62.— Galileo's air thermometer.

(*b*) You have now enclosed a definite mass of air within the glass bulb. The water in the tube prevents the air from escaping. You are prepared, therefore, to study the effect of heat upon this mass of air. First lay the palm of your hand on the bulb. Is the volume of the enclosed air affected? How? Is the pressure of the enclosed air affected? In your answer to this question, give a diagram which will make the reasons for your answer perfectly clear. Hold a burning match near the bulb for a moment. How does the effect compare with that due to the hand?

(*c*) Now make a small funnel by heating a piece of glass tubing in a Bunsen flame and quickly drawing it out. The

tubing should have a cross-section a little less than that indicated at *A* in Fig. 63, and when drawn out the funnel must be small enough to pass into the stem of the glass bulb. You will be surprised to find how easily and quickly you can make such a funnel.

By means of this funnel fill the glass bulb with water. For this purpose, the bulb should be held in a wooden clamp and the long slender capillary funnel thrust down the stem until it protrudes into the bulb. When the bulb is full and the water is rising in the stem, slowly withdraw the funnel. In this manner, you will quickly fill the entire bulb with water.

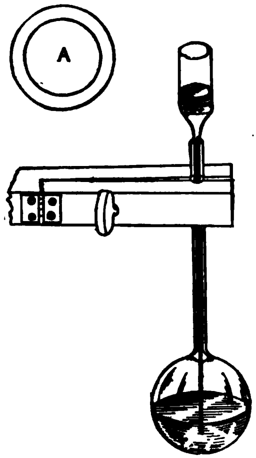

Fig. 63.—A capillary funnel, for quickly and easily filling a glass bulb, which is provided with a tube of small bore.

You have a definite mass of water upon which to experiment. Having carefully dried the outside of the bulb and having fastened it in a wood clamp, dash the flame of a Bunsen burner against it, *for an instant only.* What is the immediate effect upon the height of the water in the stem? What effect follows a moment later? Which gets hot first, the liquid or the glass bulb which contains the liquid? Does glass expand or contract, therefore, when heated? Which expands more, for the same change in temperature, glass or water? What experimental evidence for your view?

Exercise 49.—Relative Expansion of Solids

References.—Crew, 235; Hall and Bergen, 289; Wentworth and Hill, 93; Gage, 136; Avery, 229.

Apparatus.—A small vise; four strips of sheet metal each about 8 or 10 inches long and about ½ inch wide; zinc, copper, iron, and brass are suggested; three or four ordinary wire con-

nectors with a slot sawed in one end as indicated in Fig. 64; a Bunsen flame; a stand in which to clamp a small pointer or index.

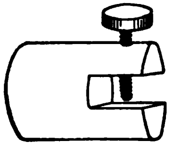

FIG. 64. — Slotted wire-connector; a light clamp for binding metal strips.

Problem. — To examine these four metals in pairs, and to arrange them in the order of magnitude of their coefficients of expansion.

Experiment. — (*a*) First be sure that you can distinguish the four different metals which you are given to examine. Then fasten a small vise to the edge of the table, and in this, clamp together two of the metal strips as shown in Fig. 65. Fasten these strips together with small clamps at intervals of not more than 2 or 3 inches.

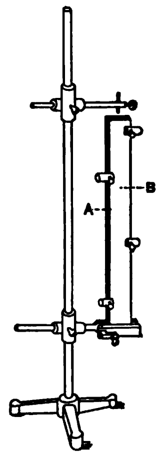

FIG. 65. — Two metal strips arranged to show difference of expansion.

If, now, these two strips expand at the same rate, there will be no tendency for them to slip one over the other; they will, therefore, remain straight. But if one metal expands more than the other there will be a tendency for that metal to slip over the other. But it cannot slip if the two are tightly clamped together. The result will be, therefore, that the strip which expands more will accommodate itself to circumstances by taking the *outside* of a curve, leaving the other strip on the *inside* of the curve.

If the metals do not bend when heated, we may, therefore, infer that they have the same coefficient of expansion, that is, that they increase by the same percentage length for any given change in temperature. If the metals *do* bend, we know that their coefficients of expansion are different. Not only so, but we can infer, *from the direction in which the bending occurs,* which of the two metals has the *greater* coefficient of expansion. Clamp a small pointer, say a bit of wire, in a stand and bring one end of this index

immediately over the upper end of the metal strips. This will enable you to detect a very slight bending of the strips.

(*b*) You are now prepared to examine these metals and arrange them in the order of magnitude of their coefficients of expansion. Pass a Bunsen flame quickly, from one side to the other, over the edge of the metal strips; but only for a moment or two, so as to heat the metals *gently* and *equally*. You will be surprised, possibly, to see the top of the strip move to one side or the other.

Let us call the two metals A and B, as indicated in Fig. 65, and let us suppose that when the metals are equally heated the top moves toward the side on which B lies. Which, therefore, of the two metals has the greater coefficient of expansion, A or B? See whether, on cooling, the top of the metals comes back to the index. If the top does not come back, it is probable that you have not clamped the metals tight enough to prevent slipping. By holding the flame, first against one metal then against the other, you can make the strip bend in either direction. How do you explain this?

How could you employ a pair of metal strips, such as these, to indicate when the temperature of a room is too high or too low?

(*c*) Call the four metal strips A, B, C, and D. Try them in pairs, as follows: A and B, A and C, A and D, B and C, B and D, C and D. After examining each pair with the flame, record your result as follows: —

$$\text{Coefficient of } B > \text{Coefficient of } C,$$
$$\text{Coefficient of } B < \text{Coefficient of } D,$$
$$\text{etc.}$$

Only, instead of using letters, record of course the names of the metals.

(*d*) Finally, arrange your metals by name in a column so that the one at the top shall have the largest coefficient of expansion, the one at the bottom the smallest, and the intermediate ones shall also be in the order of their magnitudes.

Exercise 50. — Fixed Points of a Mercury Thermometer

References. — Crew, 222; Avery, 220–221; Carhart and Chute, 184; Hall and Bergen, 292.

Apparatus. — Centigrade thermometer, graduated from the freezing-point to the boiling-point, or, preferably, a degree or two higher; small battery jar; snow or finely crushed ice; retort-stand with ring; hypsometer, as in Fig. 66; rubber band; Bunsen burner; string.

Problem. — To find the error in the freezing-point and in the boiling-point of a mercury thermometer, as marked on the glass stem.

Experiment. — (*a*) *Freezing-point.* Suspend the thermometer from the ring of the retort stand by a string. Fill the battery jar with finely crushed ice, and add about enough water to fill the lower half of the jar. Make a vertical hole in the ice with a lead pencil, and insert the thermometer stem, with the bulb about in the middle of the jar. Pack the ice well around the stem. Read the thermometer occasionally, by raising it just far enough to bring the zero mark to the surface. When the mercury has sunk to 1°, begin to take readings once a minute and continue until three successive readings are the same, to a tenth of a degree. Record the last of these readings as the reading of your thermometer in melting ice.

The temperature of melting ice is practically constant, and is denoted by 0° on the centigrade scale. To find the error of the freezing-point marked on the thermometer stem, we have

$$\text{Error of freezing point} = \text{Thermometer reading in melting ice} - \text{Temperature of melting ice.}$$

(*b*) *Boiling-point.* To test the boiling-point, the thermometer is exposed to the steam from boiling water. Suspend the thermometer within the inner tube of the hypsometer, passing the stem through the cork at the top. If the cork fits the stem loosely, slip a rubber band over the stem, just above the cork.

The 100° mark should project only one or two degrees above the cork, so that as much of the stem as possible is exposed to the steam.

Steam from water boiling in the can passes up through the inner tube and down through the outer tube, so that the inner tube and the steam in it are protected from the cooling effect of the air of the room.

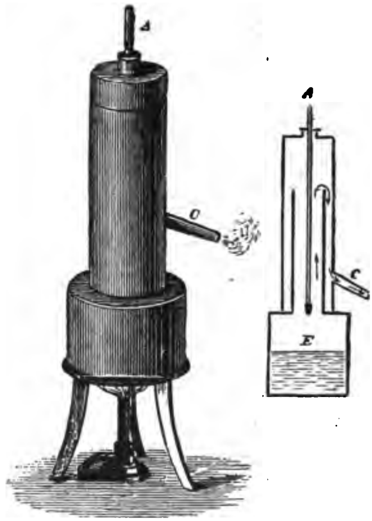

Fig. 66. — Hypsometer, an instrument for heating thermometers to the temperature of boiling water.

Fill the boiler about a quarter full of water, and heat it over a Bunsen burner. After the steam has been escaping freely for several minutes, read the thermometer. Also read the barometer. When the barometer stands at 76 cm., the boiling-point of water is 100° C. At higher pressures the temperature of steam is higher, and at lower pressures it is lower, the change either way being nearly 0°.37 C. for each centimetre of change in the height of the barometer. Thus, if the barometer reads 76.4 cm., the boiling-point of water is

$$100° + (0.4 \times 0°.37) = 100°.15.$$

Knowing the barometric height, calculate the boiling-point at the time of your experiment.

To find the error we have

$$\text{Error of boiling-point} = \text{Thermometer reading in steam} - \text{Temperature of steam.}$$

Thus the error is positive when the thermometer reads too high, and negative when it reads too low.

Record your results as in the following illustration:

Height of barometer = 75.4 cm. No. of thermometer, 27.

Thermometer reading in melting ice	0°.3 C.
Temperature of melting ice	0 .0
Error of freezing-point	+0°.3
Thermometer reading in steam	99°.5 C.
Temperature of steam	99 .78
Error of boiling-point	−0°.28

(c) After testing the boiling-point determine the freezing-point a second time. Has the reading in ice changed? If so, is the bulb larger or smaller than before heating?

Exercise 51. — Half and Quarter Points of a Thermometer

Reference. — Crew, 222.

Apparatus. — A piece of thick-walled "capillary" glass tubing about 25 cm. long and $\frac{1}{2}$ to 1 mm. in internal diameter; the tube should be graduated from 0 to 100°, like the stem of a centigrade thermometer,* the graduations extending to within about 2 cm. of the ends of the tube; mercury trough, as in Fig. 67, made of a narrow block of wood with a channel $\frac{1}{2}$ inch wide and about the length of the tube, and having an inclined bottom $\frac{3}{8}$ inch deep at one end, and flush with the top of the block at the other end; 3 inches of soft rubber tubing, to fit air-tight over the end of the glass stem; a little mercury; mercury tray, that is, a tight shallow wooden box open at the top in which the mercury will be caught in case of accident.

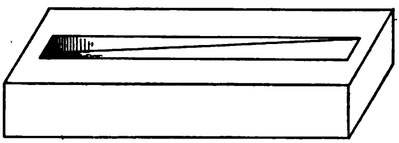

Fig. 67. — A small wooden trough, convenient for filling a tube with mercury.

* The use of an actual thermometer is not here suggested for the very excellent reason that the "breaking of the mercury column" is too apt to be accompanied by the breaking of the thermometer.

Problem. — To learn how to divide a given length of tube into two parts of equal volume, as is required in determining the half and quarter points of a thermometer.

Experiment. — (*a*) *The 50° point.* If we regard the graduated tube as the stem of a thermometer, on which the freezing and boiling points have been correctly marked, the problem is, first, to find whether the 50° mark, that is, the "half point," divides the volume included between the fixed points into two equal parts; and if not, to find the error in its position.

Slip the rubber tube about 5 mm. over one end of the stem. Lay the stem in the trough (Fig. 67), the end opposite the rubber tube being at the deepest part. Pour in mercury sufficient to cover this end. To avoid spilling mercury the *trough must be placed in the mercury tray before filling it.* After the tube is filled it should be kept over the tray, and no mercury should be carried beyond the sides of the tray during the experiment. Now press the stem down with the left hand, and grasp the rubber tube tightly between the thumb and forefinger of the right hand. By keeping the sides of the rubber tube pressed tightly together, and sliding the forefinger backward over the thumb, you will be able to draw a thread of mercury into the glass stem. Make the column just about long enough to reach from the 0° mark to the 50° mark, — not more than a degree longer or shorter than this.

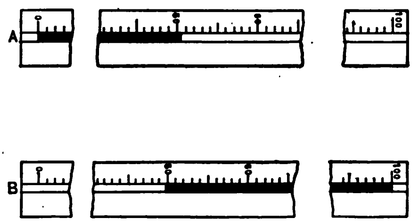

Fig. 68. — Rudberg's method of dividing the volume of a tube into two equal parts.

Now, holding the stem with the zero end at the left, slide the thread of mercury along until its left-hand end coincides accurately with the 0° mark. Read, to a tenth of a degree, the position of the right-hand end of the thread. For example, at *A*, Fig. 68, the reading is 50°.4, as recorded below. Move the thread along the tube until its right-hand end coincides accu-

rately with the 100° mark, and read the position of its left-hand end. This corresponds to the position shown at *B*, Fig. 68, where the reading is 49°.8. Since the volume of the mercury column is the same in both positions, provided its temperature has not changed, the *mean* of the two readings just taken (*i.e.* the point halfway between them), is the correct position of the half point, which in the above illustration is 50°.1. What, therefore, is the *error* in the 50° point, as marked on the stem?

(*b*) *Quarter Points.* Draw into the stem a thread of mercury just about long enough to reach from the 0° mark to the 25° mark. Find the error of the 25° mark as described in (*a*), except that the "fixed points" are now to be the 0° mark, and the correct position of the 50° mark, as found in (*a*). Thus, in the above illustration, the right-hand end of the mercury thread would be placed, not at 50°, but at 50°.1. Then find the error of the 75° mark, using as "fixed points" the correct position of the 50° mark and the 100° mark.

Record as follows:

Tube No. 16

50° point —	
Reading of right end (left end at 0°) . . .	50°.4
Reading of left end (right end at 100°) . .	49 .8
Correct position of 50° mark	50°.1
Error of 50° mark	−0°.1 (too low)
25° point —	
Reading of right end (left end at 0°) . . .	24°.7
Reading of left end (right end at 50°.1) .	25 .2
Correct position of 25° mark	24°.95
Error of 25° mark	+0°.05 (too high)
75° point —	
Reading of right end (left end at 50°.1) .	75°.0
Reading of the left end (right end at 100°) .	75 .1
Correct position of 75° mark	75°.05
Error of 75° mark	−0°.05 (too low)

Exercise 52. — Boiling-point of a Solution — A Further Study of Thermometry

References. — Crew, 244; Carhart and Chute, 224; Avery, 240; Rowland and Ames, 106.

Apparatus. — A distilling flask (or an ordinary Florence flask) to hold about 16 to 20 ounces of water; a Bunsen flame; tripod (or ring-stand) with asbestos (or wire gauze) plate, for heating flask; thermometer graduated to 110° or higher; ½ pound table-salt; 8 or 10 inches of small glass tubing for escape pipe; perforated cork.

Problem. — To discover whether there is any difference between the temperature of a boiling solution and the temperature of its vapor; and also to determine whether the boiling-point of a solution varies with the *amount* of salt dissolved in it.

Experiment. — (*a*) Arrange a thermometer in the cork of a flask as indicated in Fig. 69. Fit into the cork also a small glass "escape pipe" to carry off the steam. Put enough water into the flask to half fill it. Heat the water with a Bunsen flame; and, when it is thoroughly boiling, record the temperature of the vapor (steam) just over the water.

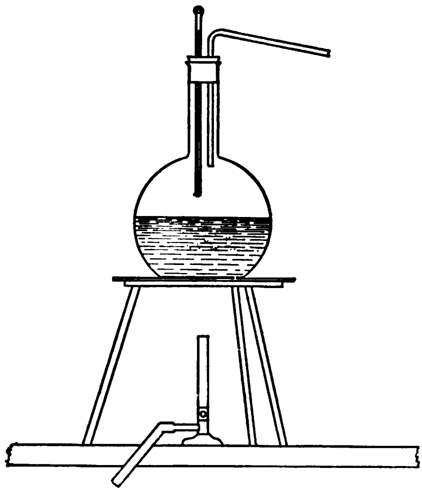

Fig. 69. — Apparatus for showing that the boiling-point of water is affected by a salt dissolved in it.

(*b*) Now push the thermometer down through the cork, so that its bulb is immersed in the boiling water. Measure and record the temperature of the boiling water.

(*c*) Remove the cork — gently, with your handkerchief — and pour into the water about one tablespoonful of ordinary salt. Now measure and record the temperature of the steam over this solution. Next, lower the thermometer into the solution and measure its temperature while boiling.

(*d*) Pour in another tablespoonful of salt and measure again the temperature of the steam over the solution and the boiling-point of the solution.

(*e*) Repeat these observations after having put in a third spoonful of salt.

Record your observations in a neat form as follows:

Temperature of steam over boiling water	=
Temperature of boiling water	=
Temperature of steam over salt solution (1 portion)	=
Temperature of salt solution (1 portion)	=
Temperature of steam over salt solution (2 portions)	=
Temperature of salt solution (2 portions)	=
Temperature of steam over salt solution (3 portions)	=
Temperature of salt solution (3 portions)	=

Why is it that in testing thermometers the "100° point" is always determined by placing the bulb in the *steam* and *not* in the *water?*

SECTION 2. — TRANSFER OF HEAT

Exercise 53. — Convection Currents

References. — Crew, 227; Rowland and Ames, 101; Avery, 228; Hall and Bergen, 286; Carhart and Chute, 200–201; Wentworth and Hill, 115–118.

Apparatus. — Two U-tubes, one of which will fit easily into the other, as indicated in Fig. 70. The two arms of each tube should be equal in length. A wood clamp; a Bunsen burner; a test-tube.

Problem. — To study the currents which are produced in fluids by differences of temperature.

Experiment. — (*a*) Fasten the larger of the two U-tubes in a wood clamp, and fill the tube with water, as shown in Fig. 70. Fill the smaller U-tube with water, and, placing your fingers over the ends, quickly invert it into the larger tube, as you would a siphon. Generally you will find a small air-bubble at the top of the inverted tube; but this will do no harm so long as there is a complete circuit of water. But, of course, the air-bubble must not be large enough to extend clear across the tube. You can put these tubes together still more easily by holding them both in a bucket of water.

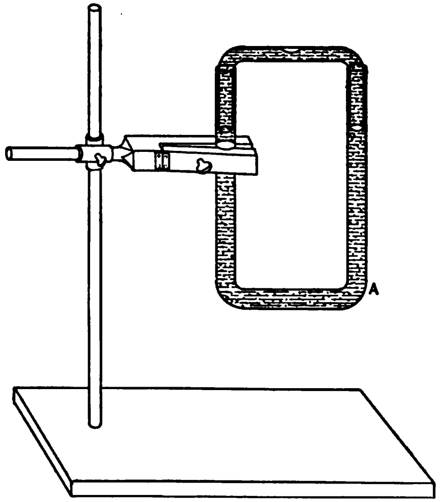

Fig. 70. — Apparatus to illustrate continuous convection currents.

Next, take a burnt match and rub up the charcoal into small particles. Place these in the water and stir them up by gently raising or lowering the inverted tube. These small black suspended particles will enable you to detect currents in the water, if there are any.

(*b*) Carefully dry the outside of the tubes, and apply a flame very cautiously to the lower part of one side, say at the point *A* in Fig. 70. Observe the liquid in the upper part of the circuit. Which way is it flowing? Does it continue to flow after the flame is removed? Why? Now apply the flame to the side of the circuit opposite *A*. What effect does this produce upon the current? Make a sketch of your apparatus, and indicate by arrows the direction of the current produced by a flame at *A*.

In your report cite two cases in which convection currents are met in daily life.

(*c*) Take a test-tube two-thirds full of cold water, and shake up in it the charcoal from one or two burnt matches. Hold the test-tube in a slightly slanting position, and heat the upper side *for a moment* with a Bunsen flame. Sketch the general trend of the currents which you observe in the water.

SECTION 3. — SOME EFFECTS OF HEAT

Exercise 54. — Coefficient of Linear Expansion

References. — Crew, 235; Hall and Bergen, 295; Carhart and Chute, 210; Wentworth and Hill, 96; Avery, 232; Gage, 137.

Apparatus. — The coefficient of expansion apparatus shown in Fig. 71; the expanding solid is here a brass (or preferably, an aluminium) tube, which is to be heated by passing steam through it; near each end of the tube, a pin of stout brass wire is passed through the tube, at right angles to its length; one of these pins is held in a fixed position, the other presses against the short arm of a lever, whose long arm moves across

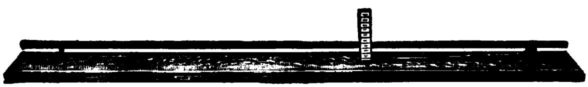

Fig. 71. — An apparatus to measure the change of length which accompanies change of temperature.

a scale of millimetres; thus any change in the length of the tube is several times magnified; steam-boiler, such as may be made of a half-gallon oil-can: thermometer; Bunsen burner; iron tripod; 2 feet of old rubber tubing, to connect the boiler with the metal tube; metre stick, and preferably a flannel jacket for the metal tube.

Problem. — To find the numerical value of the coefficient of linear expansion for a metal.

Experiment. — (*a*) The **coefficient of linear expansion** of a substance is defined as the elongation per unit length, per degree change in temperature. Thus if a rod l cm. long increases in length by e cm. when heated through t degrees, the coefficient of linear expansion, a, is given by the formula,

$$a = \frac{e}{lt}.$$

To find l, measure with a metre stick the length of that part of the tube between the two pins.

(*b*) Now find the temperature of the tube while cool by inserting the bulb of a thermometer in one end of the tube. When the mercury has become stationary, read and record the temperature. Call it $t_1°$. Read also the position of the pointer on the upright scale; this may be called r_1.

(*c*) Fill the boiler about a quarter full of water, and set it over a burner to heat. Connect the "fixed" end of the metal tube to the boiler with rubber tubing. Allow a current of steam to pass through the tube for two or three minutes, until the tube is thoroughly heated. For the purposes of this experiment, it will be sufficiently accurate to take the boiling-point of water as 100° C. This will not be the mean temperature of the tube through which the steam is passing, but will perhaps be sufficiently near to it for the purposes of this experiment. By wrapping the tube with flannel its temperature can be made to approximate still more closely to that of steam. Owing to the expansion of the tube, the position of the pointer has now changed; make a reading of its new position before removing the burner from beneath the boiler. Call this reading r_2.

(*d*) To find the elongation, e, it is necessary to know the ratio of the long arm of the lever to the short arm. In finding the length of the long arm, measure from the fulcrum to the *edge* of the vertical scale. Take particular care to measure the short arm accurately. Between what two points is its length to be measured? Record the length of each arm, and

find their ratio. The difference between the pointer readings, $r_2 - r_1$, divided by the ratio of the lever arms, will be the elongation.

(*e*) Having determined the quantities l, e, and t, calculate the coefficient of linear expansion of the metal.

Record as in the following illustration:

Length of tube, l,	= 88.7 cm
Material of tube, brass.	
Pointer reading (tube cool)	= 8.20 cm.
Pointer reading (tube hot)	= 6.50 cm.
Difference of readings	= 1.70 cm.
Temperature when cool, t_1,	= 18°.2 C.
Temperature when hot, t_2,	= 100°.0 C.
Change of temperature, t,	= 81°.8.
Length of long lever-arm	= 32.2 cm.
Length of short lever-arm	= 2.4 cm.
Ratio of long arm to short arm	= 13.4.
Elongation, e,	= 0.127 cm.

Coefficient of expansion of brass, $\frac{e}{lt} = 0.0000176.$

Exercise 55. — Coefficient of Cubical Expansion of a Gas

References. — Crew, 237, 240, 241; Avery, 231–232; Rowland and Ames, 105; Carhart and Chute, 208–210 (*a*); Hall and Bergen, 299; Wentworth and Hill, 97; Gage, 137.

Apparatus. — Six inches of glass tubing of about $\frac{1}{16}$ inch inside diameter. One end of the tube is sealed up, and into the other is introduced a thread of mercury about 1 cm. long by slightly warming the tube and dipping the open end into mercury; the mercury drop is then to be placed about two-thirds of the length of the tube from the sealed end. This is easily done

by thrusting a fine capillary tube through the mercury drop to allow air to pass into or out of the closed part of the tube. The air in the tube must be dry. Be careful, therefore, not to introduce moisture by blowing through the capillary tube. Glass beaker, six or seven inches tall; thermometer; stirrer made of a ring of sheet metal, provided with a handle of stiff brass wire, which should be bent backward near the top, so that the stirrer, when not in use, may hang on the edge of the beaker without touching the bottom, otherwise the beaker is likely to be cracked by heat; retort-stand, with ring, clamp, and asbestos plate; Bunsen burner; small rubber bands. These bands are easily made by cutting slices off the end of a "pure gum" tube with scissors.

Problem. — To find the coefficient of cubical expansion of air at constant pressure.

Experiment. — (*a*) Fill the beaker with water, insert the stirrer, and place the beaker on the asbestos over the burner, which is not yet to be lighted. Fasten the tube to the thermometer with rubber bands, and immerse them in the water, as shown in Fig. 72.

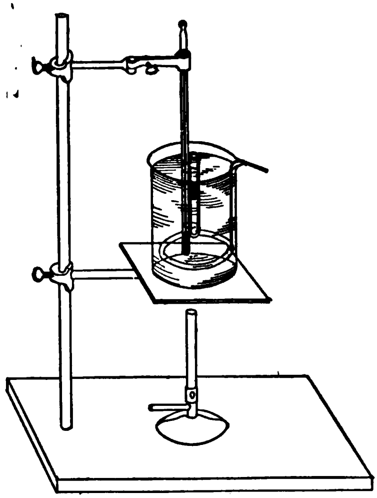

Fig. 72. — **An apparatus to measure the change of volume which accompanies change of temperature.**

In order to find the coefficient of expansion we must observe the change of volume of the enclosed air when its temperature is increased by a known amount. For this purpose we may let the *length* of the air-column represent its volume, using as a scale of lengths the marks on the thermometer stem. In this way these marks serve a double purpose. Place the lower end of the air-column

opposite some one of the lower marks on the thermometer stem, say $-10°$, so that the enclosed air may remain entirely under the water throughout the experiment. Stir the water thoroughly; read and record its temperature. Also read and record the length of the column of enclosed air in terms of thermometer divisions. You will find that the mercury nearly always adheres somewhat to the sides of the tube, and so fails to respond to slight changes of pressure. To avoid this difficulty always tap the tube lightly with a pencil before reading the position of the mercury drop.

(*b*) Now increase the temperature of the water by about 20°, frequently tapping the tube to allow the mercury to move freely. Lower the flame while stirring continually, and *keep the temperature constant* for about a minute, so that the air may have time to reach the temperature of the water. Then read and record the temperature and length of the air-column, first tapping the tube.

The coefficient of cubical expansion is defined as the change in volume per unit volume, per degree change in temperature. Thus, if the volumes at $t_1°$ and $t_2°$ are V_1 and V_2, respectively, the coefficient is

$$b = \frac{V_2 - V_1}{V_1\,(t_2 - t_1)}.$$

The volume as measured in this experiment is numerically equal to the length of the air-column expressed in divisions of the thermometer stem.

Find from your observations the change of temperature to which you have subjected the enclosed air; also find the corresponding change of volume. Hence calculate the change which each unit of volume undergoes for one degree of temperature change, *i.e.* calculate the coefficient of expansion.

(*c*) Take about four more readings, as in (*b*), increasing the temperature each time about 10°. Combine each of these observations with the *first* observation; viz. that made in (*a*), and thus calculate from each a new value for the coefficient of

expansion. Take the mean of these determinations as your value.

Record your results in tabular form.

Exercise 56. — Melting-point of a Solid

References. — CREW, 243; ROWLAND AND AMES, 106; CARHART AND CHUTE, 214–215; AVERY, 235; HALL AND BERGEN, 316; WENTWORTH AND HILL, 99.

Apparatus. — Six inches of $\frac{1}{4}$-inch glass tubing, with one end drawn out to a narrow portion and sealed off; the narrow portion is to be filled with paraffin wax. Thermometer; retort-stand with ring to hold beaker and clamp to hold thermometer; Bunsen burner; asbestos plate some 6 inches square; 4 to 8 ounce glass beaker; perforated cork to adapt thermometer stem to clamp.

Problem. — To illustrate the general fact that solids melt at quite definite temperatures, and in particular to determine the temperature at which paraffin melts.

Experiment. — (*a*) Fasten the paraffin tube to the stem of the thermometer with rubber bands, so that the narrow portion containing the paraffin is opposite the bulb, as in Fig. 73. Lay the asbestos plate on the ring of the retort-stand, about 3 inches above the top of the burner, and on the asbestos set a beaker nearly full of water. Support the thermometer by inserting the upper end of the stem in a cork, which in turn is

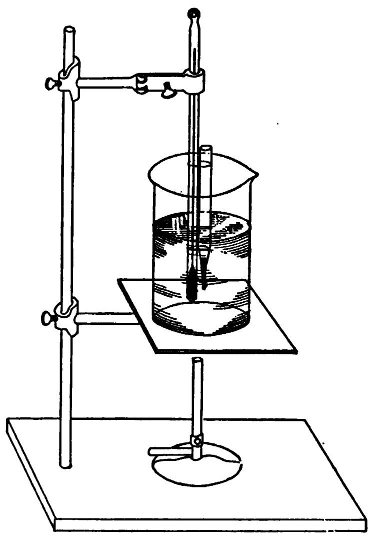

FIG. 73. — Melting-point of paraffin.

held by the clamp of the retort-stand. The thermometer bulb and the paraffin are to be well immersed in the water. Start the burner with a *low* flame, so that the beaker and its contents will be heated gradually.

Note accurately the temperature at which the wax *just begins* to be transparent at the *lowest point* of the tube. Record this temperature, and immediately remove the burner without waiting for the rest of the paraffin to melt.

(*b*) As the water surrounding the paraffin cools, the paraffin will soon begin to solidify. Note accurately the temperature at which solidification occurs in the *lowest point* of the tube, — the same point at which you previously observed the melting. Take the mean of the two observations as the melting-point.

Make at least five pairs of readings as described, recording your results in tabular form. Finally take the mean of all the melting-points so determined.

Does glass conduct heat well or badly? (Consult a table of conductivities, as on p. 189 of Crew's *Elements of Physics*.) Which, then, will be the warmer, while you are heating the beaker, the paraffin in the tube or the surrounding water? Which will be the warmer while the beaker is cooling? Do your results show that your answers are probably correct? Note that the bulb of the thermometer presents a large surface to the water, so that the mercury reaches the temperature of the water much more quickly than the paraffin.

Exercise 57. — Change of Boiling-point with Pressure

References. — Crew, 244–245; Rowland and Ames, p. 118; Avery, 240; Carhart and Chute, 224; Wentworth and Hill, 104; Gage, 150.

Apparatus. — As in Fig. 74. *A* is a flask of 8 or 10 ounces capacity, furnished with a two-holed rubber stopper, and arranged on an asbestos plate over a Bunsen burner. *B* is a one-quart Woulff's bottle with three necks, each fitted with a perforated rubber stopper. *B* is connected with *A* by a bent glass tube.

A second tube, leading from the *bottom* of the Woulff's bottle is connected by thick-walled rubber tubing with a filter pump. To the remaining neck of the Woulff's bottle is attached a mercury pressure-gauge *C*, made of a bent glass tube, whose longer arm, about 33 inches in length, dips into a vessel of mercury. At *D* is a short piece of ordinary rubber tubing, closed by a Mohr pinch-cock. Metre stick. A good filter pump may be purchased for about $1.50, and is an instrument

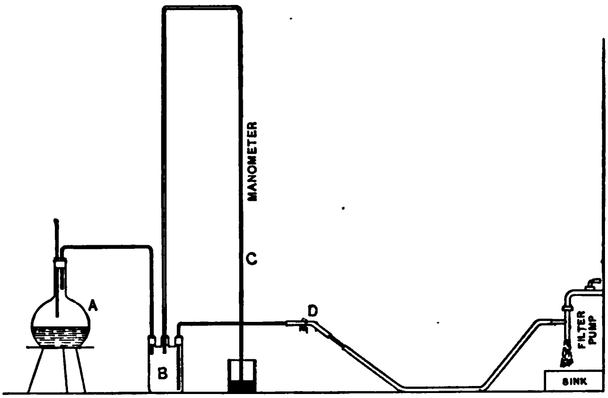

Fig. 74. — Apparatus for showing how the temperature of boiling water varies with the pressure.

whose great convenience and varied uses entitle it to a place in every laboratory. Barometer; Bunsen burner; thermometer.

Problem. — To find how the boiling-point of water is affected by change of pressure; and incidentally to explain why the height of the barometer must be taken into account when the 100° point of a thermometer is determined, as in Exercise 50.

Experiment. — (*a*) Fill the flask *A* half full of water. Pass the thermometer through the stopper, and allow its bulb to remain above the surface of the water. Open the pinch-cock, so that the interior of the apparatus is in free communication

(through the filter pump) with the outside air. Boil the water in the flask, and read the temperature of the steam. Read the barometer, in order to know the pressure at which the above boiling-point was observed.

(*b*) Close the pinch-cock and start the filter pump. Open the pinch-cock for a moment, thus allowing the filter pump to slightly exhaust the air in the apparatus. The decrease of pressure will be shown by the mercury rising in the gauge tube *C*. To measure the height of the gauge column, fix a metre stick vertically alongside the gauge, with its lower end resting on the table. Reduce the pressure enough to cause the mercury in the gauge to rise 8 or 10 cm. By properly managing the pinch-cock, you will be able to keep the column very nearly at a fixed height, while the water is boiling, for a long enough time to allow you to read the temperature. Record the temperature. Also record the height, above the table, of the mercury in the gauge tube, and the corresponding height of mercury in the reservoir. The difference between these heights will be the change of pressure, expressed in centimetres of mercury. Hence calculate and record the pressure corresponding to the boiling-point just read.

For example, if the barometer reading is 76 cm., and the mercury in the gauge tube stands 10 cm. above that in the reservoir, the pressure in the apparatus is $76 - 10 = 66$ cm.

(*c*) Determine the boiling-point, as in (*b*), for several other pressures, down to the lowest pressure the filter pump will produce. Record your results in a table.

(*d*) While the water is boiling at a low pressure, stop the pump, and admit air by opening the pinch-cock. What is the effect on the boiling of the water? How do you explain this effect?

(*e*) Plot a curve from the results of your experiment, taking pressures as abscissas, and boiling-points as ordinates. From your curve determine at what temperature water will boil on a mountain top, where the barometric height is 65 cm.

Exercise 58. — Change of Vapor-pressure with Temperature

References. — Crew, 244–245; Rowland and Ames, p. 118; Hall and Bergen, 324.

Apparatus. — A U-tube having one arm closed, the other arm longer and open as indicated in Fig. 75; the inside diameter of the tube may well be about $\frac{1}{4}$ inch, and the length of the short arm about 6 inches. A very large test-tube, say $1\frac{1}{2}$ inches in diameter, or a tall slender beaker; mercury to fill closed arm of tube; retort-stand and clamp with Bunsen burner for heating test-tube or beaker; thermometer; few drops of alcohol.

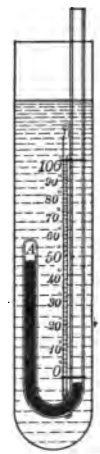

Fig. 75. — A simple device for observing changes of vapor-pressure which accompany changes of temperature.

Problem. — To observe the phenomenon of vapor-pressure and in particular to measure the vapor-pressure exerted by alcohol at different temperatures.

Experiment. — (*a*) Into a U-tube closed at one end pour mercury to a depth somewhat like that indicated in Fig. 75. Then pour over the top of the mercury a few drops of alcohol, so that it stands, say, $\frac{1}{8}$ or $\frac{1}{4}$ inch deep over the mercury; and by inclining the tube you will be able to get some of the alcohol into the short arm of the tube, while at the same time you let practically all of the air out. The mercury will then stand higher in the short arm than in the long one; in fact it will practically *fill* the short arm.

Next attach a thermometer to the long arm of the tube, which you can easily do by slipping two rubber bands over the thermometer and the tube, thus lashing the two together. You have now a little alcohol enclosed at *A*, while the mercury in the tube acts as a manometer to measure the pressure which is exerted upon the alcohol by its vapor.

To get the change of vapor-pressure with temperature you

have only to immerse the U-tube and thermometer in a glass vessel (test-tube or beaker) filled with water to a depth sufficient to cover the short arm of the tube.

(*b*) Now heat this vessel of water; and, as its temperature rises, read the thermometer and the difference of level of the mercury in the two tubes. But before reading the thermometer, stir the liquid thoroughly so as to make its temperature uniform throughout. It is well to remove the flame just before you read the thermometer.

The scale on the thermometer may be used to measure the difference in level between the two mercury columns. Read the temperature for every 3° of change, heating the tubes until finally the alcohol vapor pushes the mercury all the way round the bend of the tube.

Record your observations in neat tabular form as follows:

Temperature	Difference of level in mercury columns	Vapor-pressure

To get the vapor-pressure you must add to (or subtract from) the height of the barometer the difference in level between the two mercury columns expressed in centimetres. For this purpose the height of the barometer may be taken as 76 cm.

When the mercury stands at the same height in each arm, what is the pressure on the vapor over the alcohol? If the alcohol were open to the air, what would happen at this temperature? What is the vapor-tension of water at 100°? Suppose you had only 2 or 3 drops of a liquid, how could you, by the above method, determine its boiling-point? What is the vapor-pressure of water at 0° C. and at 50° C.? (See tables in *Encyclopædia Britannica*, art. *Heat.*)

Exercise 59. — Thermal Phenomena accompanying Evaporation and Solution

References. — Crew, 249–250; Rowland and Ames, p. 120; Carhart and Chute, 216–221; Hall and Bergen, 332; Wentworth and Hill, 111, 113; Gage, 154–156; Avery, 236–238.

Apparatus. — Two test-tubes of medium size; about 1 foot of ¼-inch glass tubing; some 5 or 6 g. each of concentrated sulphuric or hydrochloric acid, sodium hyposulphite, granulated or powdered, and sulphuric ether; a watch-glass; a large cork; a thermometer; a small vessel of water (preferably an ordinary wash-bottle) at the temperature of the room.

Problem. — To observe the changes of temperature which accompany changes of state.

Experiment. — (*a*) Take a dry test-tube and fill it to a depth of 1 inch, approximately, with "hypo," such as photographers use. Place in this a thermometer to assure yourself that the "hypo" is near the temperature of the room. Into another test-tube pour a mass of water, which is about twice that of the "hypo," and assure yourself that this water is near the temperature of the room. Having the thermometer in the "hypo," pour this water over the "hypo." Read and record the lowest temperature reached. How do you explain this fall in temperature? Has the mixture as a whole lost any energy? Reason for your opinion. You started with the "hypo" as a solid. In what condition is the "hypo" at the end of the experiment? Name two other instances in which heat is evidently required to change a solid into a liquid body.

(*b*) Fill a test-tube to a depth of about ½ or ¾ inch with water at the temperature of the room. Measure and record the temperature of this water. Now, holding the test-tube near the top, pour into the water, with great caution, an equal volume of strong sulphuric acid (oil of vitriol). Measure and record the highest temperature reached by the mixture.

Here there is no change of state; there is, however, a solu-

tion of sulphuric acid in water. Is it true, therefore, that a solution of one substance in another is *always* accompanied by a fall of temperature, as was the case in (*a*)?

(*c*) Place a few drops of water on a cork, and on this water a watch-glass, as indicated in Fig. 76. Pour the watch-glass nearly full of ether — being careful not to inhale any considerable quantity of it or to bring it near a flame. With a glass tube about 1 foot long, blow gently and steadily over the ether in the watch-glass. What happens to the ether? What change of state occurs in the ether? Does the amount of heat in the system (ether — glass — water — cork) increase or diminish? What becomes of this heat? Name two other instances in which heat is absorbed by a body which is changing from a liquid to a gas? Can you, in this way, freeze the water under the watch-glass? What good does it do to blow over the ether? Why does not the air which is already immediately over the ether do exactly the same thing as the air which you blow over it?

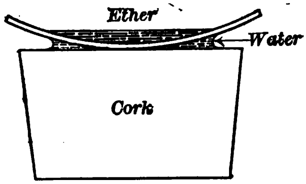

Fig. 76. — Illustrating absorption of heat which accompanies evaporation.

Why is there danger in sitting in a "draft," even when the air which makes the draft is no cooler than the air in the room?

Exercise 60. — Phenomenon of Freezing — Cooling Curve of Paraffin

References. — Crew, 243, 249; Rowland and Ames, p. 117; Carhart and Chute, 216–219; Hall and Bergen, 320; Wentworth and Hill, 110; Gage, 146.

Apparatus. — Test-tube 5 or 6 inches long; a thermometer, which is to be inserted in the test-tube, with its bulb 1 or 2 cm. from the bottom, and kept in place by passing the stem through a perforated cork which fits the top of the

test-tube; into the test-tube is poured enough melted paraffin to cover the top of the bulb to a depth of about a centimetre; beaker holding a sufficient depth of water to admit of immersing the paraffin; retort-stand, with clamp, for holding test-tube; Bunsen burner; asbestos plate; clock or watch with second-hand. For this experiment use pure paraffin having a definite melting-point; this is prepared in Germany, and is furnished by supply houses at small cost in packages of 100 g.

Problem. — To observe the effect of change of state upon change of temperature.

Experiment. — (*a*) Secure the top of the test-tube in the clamp of the retort-stand, and immerse the lower end in a beaker of water until the part containing paraffin is entirely submerged. Heat the beaker on asbestos over a Bunsen burner. Continue to apply heat until the paraffin has all melted, and has reached a temperature of 75° C., or more. Then raise the test-tube out of the water and remove the beaker, allowing the test-tube to cool in the air of the room.

As the paraffin cools, read and record its temperature to one-tenth of a degree, at intervals of half a minute. Continue to do this until the temperature has fallen to about 40° C., or to at least 15° below the melting-point of the paraffin used.

(*b*) From your record plot a curve, taking for the abscissa of each point the number of minutes since the timing began, and for the ordinate the corresponding temperature.

How do you explain the fact that the temperature remains nearly constant for a considerable time? Evidently the paraffin is hotter than the air in the room, and is therefore giving off heat to the room. Where does the paraffin get this supply of heat energy during the time in which the temperature remains constant? Does a gramme of water at 0° C. contain more energy than a gramme of ice at 0° C.? The student who can find leisure will be interested in repeating this experiment, using water instead of paraffin.

SECTION 4.—MEASUREMENT OF HEAT

Exercise 61.—Temperature of a Mixture

References.—Crew, 246, 248; Carhart and Chute, 231–233; Avery, 242–244; Gage, 130–132; Wentworth and Hill, 107–108.

Apparatus.—Two beakers of 3 or 4 ounces capacity; thermometer; measuring glass graduated in cubic centimetres; iron tripod; Bunsen burner; asbestos plate.

Problem.—A known mass of water at a given temperature being mixed with a known mass of water at a different temperature, to find the resulting temperature of the mixture. An introduction to the measurement of quantities of heat.

Experiment.—(*a*) Heat some water in one of the beakers to a temperature between 40° C. and 70° C. In the other beaker put a measured mass, m_1, of cold water. Stir this *very gently* with the thermometer, and find its temperature to one-tenth of a degree. Call this temperature t_1. Remove the warm water from over the burner, stir it a moment, and read its temperature, calling this t_2. Transfer the thermometer to the beaker of cold water, and immediately pour into this some of the warm water. Stir the mixture and read the highest temperature reached. Call this T. Measure the mass of the water in the mixture, and call it $m_1 + m_2$. Hence m_2 is the mass of the warm water added.

(*b*) Having *observed* the temperature of the mixture, T, proceed now to *calculate* it, as follows: A **calorie** is defined to be the quantity of heat absorbed by 1 gramme of water when heated 1°, or given out when 1 gramme of water cools 1°. Hence the number of calories of heat absorbed or given out by water when heated or cooled, respectively, is equal to the mass of the water in grammes, multiplied by its change of temperature in degrees. In this experiment, m_1 grammes of water are warmed from $t_1°$ to $T°$. The quantity of heat required to do this is

$$m_1(T - t_1) \text{ calories.}$$

At the same time, m_2 grammes of water are cooled from $t_2°$ to $T°$, thus absorbing

$$m_2(t_2 - T) \text{ calories.}$$

We shall assume, as is approximately true, that all the heat given out by the warm water is employed to heat the cold water. Hence these two quantities of heat will be equal, so that

$$m_1(T - t_1) = m_2(t_2 - T).$$

In your report, find the value of T in terms of m_1, m_2, t_1 and t_2; *i.e.* solve the equation for T. Having measured the four quantities in terms of which T is expressed, you can now substitute their value, and so calculate T.

(*c*) Repeat (*a*) and (*b*) about five times, varying the mass and temperature of the water used. Tabulate your results under the headings, m_1; t_1; $m_1 + m_2$; t_2; m_2; predicted value of T; observed value of T.

It is not strictly correct to assume that *all* of the heat given out by the warm water is absorbed by the cold water. Some of it warms the beaker and the thermometer and the surrounding air, and some is lost by radiation. These losses, however, are comparatively small, and with careful work your observed and predicted values of T should not, in general, differ by more than 1°.

Would you expect the observed values of T to be larger or smaller than the predicted values? Which do you find to be the larger?

SECTION 5. — APPLICATIONS OF HEAT

Exercise 62. — The Steam-engine

References. — Crew, 253–254; Carhart and Chute, 237–238; Gage, 168; Avery, 253; Wentworth and Hill, 231; Hall and Bergen, 340.

Apparatus. — Several sheets of white paper; a pencil; a triangle; a ruler divided into inches or centimetres.

Problem. — To explain the automatic feature of the steam-engine. When the steam, by expanding, drives the piston-head to one end of the cylinder, what device is employed to drive the piston back again? To make a drawing which will illustrate this device.

Experiment. — (*a*) Before proceeding with this work, it is essential that you shall have mastered the principle upon which the steam-engine operates. This mastery you must obtain either from the references cited above or from some other reference, or, better still, from actual examination of some steam-engine.

(*b*) Now make a sectional drawing of the *cylinder* of a steam-engine, that is, a drawing which will show the appearance of the cylinder when divided by a vertical plane through the piston-rod. Let the cylinder be 4 inches in length and 2 inches in diameter, inside measure; leave three openings in the cylinder, namely, one for the piston-rod and two for the steam-ports. Make the walls of the cylinder about as thick as you think they ought to be in proportion to the other dimensions of the cylinder.

(*c*) Next proceed to draw on the proper side of the cylinder a sectional view of the *steam-chest,* together with the slide-valve. The chest will have five openings in it; namely, one to admit steam from the boiler, two connecting the steam-chest with the cylinder (steam-ports, mentioned above), one for the exhaust-pipe connecting the steam-chest with the open air, and lastly, one to admit the rod which works the slide-valve.

Sketch in the slide-valve in a position such that it will admit steam from the boiler into one end of the cylinder.

(*d*) Next draw the *piston* and the *piston-head* in the correct position, remembering that the correct position is already determined by the position which you have given the slide-valve. Indicate by an arrow the direction in which the piston is moving. Put arrows on the ports also, showing the direction in which the steam is flowing in the case which you have drawn. Make your drawing clear and neat.

Letter your drawing, using the following notation:

Let *C* indicate the cylinder.
Let *P* indicate the piston-head.
Let *R* indicate the piston-rod.
Let *S* indicate the steam-chest.
Let *D* indicate the slide-valve.
Let *E* indicate the exhaust-pipe.

(*e*) It remains to explain the *automatic feature* of the steam-engine. For this purpose make a sketch of the device which is employed to move the slide-valve to and fro. This device is merely a form of crank attached to the shaft which is driven by the piston; it is called an "eccentric." A steel rod connects this crank with the slide-valve, thus rendering the engine automatic.

(*f*) In your report explain what is meant by the "dead centre" of an engine. At your earliest opportunity examine a railway locomotive at rest, and see how the cranks on the driving-wheels are arranged so as to give the locomotive no "dead centres"; in other words, explain how a locomotive can start from any position whatever.

ON THE NATURE OF HEAT

In a previous Exercise (23, pp. 53–55), we have seen that in all kinds of machinery friction is at work transforming various kinds of energy into heat. The steam-engine is a machine which is used for exactly the reverse process, namely, for transforming heat into work. An accurate study of these processes has shown that, whenever heat disappears, a certain amount of energy appears; and *vice versa*, whenever heat is produced, a certain amount of energy disappears. Furthermore, the amount of energy which disappears is always exactly proportional to the amount of heat produced. Careful measurements of this kind, made by Rumford, Joule, and others, have led to the conclusion that **heat is a form of energy.**

CHAPTER VII

MAGNETISM

Exercise 63. — Fundamental Phenomena in Magnetism

References. — Crew, 268, 262, 266, 267, 260; Rowland and Ames, 108–113; Hall and Bergen, 375–381; Carhart and Chute, 239–254; Wentworth and Hill, 240–248; Gage, 337–341; Avery, 365–368.

Apparatus. — Magnetoscope; the simplest and best form is possibly that illustrated in Fig. 77, which consists simply of a lamp chimney, a cork, and a small piece of magnetized watchspring suspended by a fibre of unspun silk. Small horseshoe magnet; small compass-needle mounted on a needle point (Fig. 79); a few inches of unmagnetized watchspring, which any repairer of watches will be glad to supply; pair of pliers; few inches of soft iron wire.

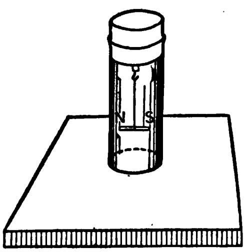

Fig. 77. — Simple form of magnetoscope.

Problem. — A qualitative study of the magnetic properties of iron, especially of the evidence for the view that magnetism is a molecular property. To distinguish between *magnetic quality* and *magnetization.*

Experiment. — (*a*) Take a magnetoscope and learn to distinguish between the north and south poles of the suspended magnet. It is well to slip or paste a small piece of paper over the north pole.

Definition. — That pole of a freely suspended magnet which points toward the north is called the **north pole** of the magnet; perhaps a better name is the north-seeking pole.

Bring near the magnetoscope a north-seeking pole. What is the effect upon the north-seeking pole of the suspended magnet? In your report state definitely what you have observed when two north poles are brought near one another, and what happens when two south poles are brought near together.

(*b*) Magnetize a piece of brittle watchspring by drawing it across the north pole of the magnet. What kind of pole (north or south) do you find at the end of the watchspring which last leaves the magnet? In order to answer this question test the magnet which you have thus made by use of the magnetoscope. Can you reverse the poles of the watchspring by drawing it in another way over the same pole of the magnet?

(*c*) Next break the magnet which you have made into a number of small pieces. Examine these pieces with the magnetoscope. Does each piece have one or two poles? Is or is not each piece a complete magnet? Do you find any evidence here for believing that magnetism is a molecular property? Explain.

(*d*) Anneal a piece of soft iron wire, say an inch or two in length, by heating it to redness in a Bunsen flame, and then allowing it to cool slowly. A piece of copper wire will enable you to hold the iron wire in the flame. Show that this annealed iron wire attracts *both* ends of the magnetoscope needle.

Definition. — A body which attracts both ends of a magnet is said to possess **magnetic quality**, but it is not magnetized.

(*e*) Magnetize a short piece of watchspring, say a piece an inch long. Bind a piece of copper wire around the watchspring so that you may hold it in the flame of a Bunsen burner until it has reached a bright red heat. When the piece of watchspring has cooled examine it for *magnetization*. Examine it for *magnetic quality*.

Exercise 64. — Study of a Magnetic Field

References. — Crew, 263; Rowland and Ames, 114; Avery, 368–369; Carhart and Chute, 255–256; Wentworth and Hill, 249; Gage, 342.

Apparatus. — Two short bar magnets, such as may be made from an old flat file, broken into 3-inch lengths, and magnetized on the poles of a dynamo; pepper box containing fine iron filings; three sheets of "rapid printing" blue print paper,* about 8 by 10 inches; piece of $\frac{7}{8}$-inch board somewhat larger than the paper; this board should have a lengthwise groove along the middle of its upper surface a trifle wider than the magnets, and of a depth equal to the thickness of the magnets, so that the magnets when placed in the groove will have their upper surfaces flush with the top of the board; tray or bucket of water in which to wash prints.

Problem. — To study the region about a magnet; in particular, to study the direction of the magnetic force at each point in this region.

Experiment. — (*a*) Keep the blue print paper in the dark — for instance, between the leaves of a large book — until you are ready to use it. Choose for the experiment a part of the room not exposed to bright daylight, as the paper is rapidly affected by light.

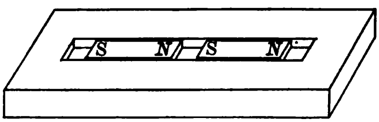

Fig. 78. — Convenient arrangement for mapping out a magnetic field by means of iron filings.

Lay one of the magnets in the groove of the board, and place over it a sheet of blue print paper, blue side up. Pin this to the board at the corners to keep it flat. Sift iron filings evenly over the paper, holding the sifter about a foot above the table. The filings will arrange themselves in regular curves, following

* This paper may be bought in rolls ten yards long and one yard wide at about $1.00 a roll.

the lines of force of the magnetic field. The best results are obtained by sprinkling a thin layer at first, afterward adding more in those spots where they seem to be most needed. The lines of force should be sharply outlined.

Now lift the board and its contents without jarring, and place it near a window in a good light. Let it remain until the yellowish color of the paper has changed to a bluish gray. This should require in good diffused daylight from 15 to 20 minutes. If direct sunlight is available the printing will take much less time; one or two minutes will probably be sufficient. When the printing is finished pour off the filings, and soak the print in three or four changes of water, leaving it three or four minutes in each, or soak the print about five minutes in running water; then hang it up by one corner to dry, and you will have a permanent map of the magnetic field.

(*b*) Map as above the field of two short magnets with their axes in the same straight line, and their ends $1\frac{1}{2}$ or 2 cm. apart (1) with unlike poles together; (2) with like poles together. Do you find any of these lines running from a north pole to a north pole or from a south pole to a south pole?

Alternative Method.—If preferred paraffined paper may be used instead of blue print paper, though the latter is much more satisfactory. Dip a sheet of paper into a dish of melted paraffin, and hang it up to drain off. Lay the paper thus prepared over the magnet, and sift iron filings over it, as described above. Pass the flame of a Bunsen burner rapidly over the sheet, so that the paraffin is melted. When it has cooled the filings are held firmly imbedded in the paraffin.

Exercise 65.—Study of the Earth's Magnetic Field

References.—CREW, 263, 264, 299; ROWLAND AND AMES, 115; CARHART AND CHUTE, 258–262; AVERY, 383; GAGE, 345.

Apparatus.—A small pocket compass, or short magnet, say one-half inch long, mounted on the point of a sewing needle as in Fig. 79. These magnets may well be made of Stubs's steel

wire about 1 or 2 mm. in diameter. The sharp end of a sewing needle placed upright in a small lead base makes an excellent pivot. The temper of the steel wire should be drawn, the steel bent as indicated in the figure, and a bearing made on the under side by means of a prick punch. Lastly the temper must be restored to the steel wire. In addition to this magnet there will be needed a large sheet of paper (the finer grades of wrapping paper answer very well), a strip of "sheet tin" about 12 inches long and 1 inch wide.

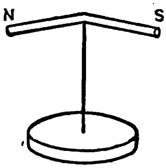

FIG. 79. — Small magnet for mapping magnetic fields.

Problem.—To plot the direction of the lines of force in a limited region of the earth's magnetic field; and to show that the earth's field is strong enough to magnetize a piece of iron by induction.

Experiment. — (*a*) Fasten down on the table top a large sheet of paper, using either pins, thumb-tacks, or a small bit of wax. Place a small compass-needle anywhere on the paper; and with your pencil mark a point as nearly as possible directly under the *north* pole. Now move the compass-needle along until its *south* pole stands as nearly as possible over the mark which you have just made. Again mark a point just under the north pole of the compass-needle; and again move the compass in the direction in which the north pole points until the south pole lies over the point you have last made. Proceed in this way until you have reached the edge of the paper. Connect this series of dots with a continuous line. This is called a **line of force**. For its direction at every point is the direction of the compass at that point.

(*b*) Now begin again and trace other lines over the paper until you have covered the entire sheet with, say about twenty lines of force, traced out in this way. Choose your points of starting so as to distribute the lines of force evenly over the entire sheet. Put an arrow on each line indicating the north direction. Make a reduced copy of the diagram on one page of your report.

(c) Take a narrow strip of "tin," which is really sheet-iron coated with tin, and mark one end of it either by pasting a small label on it or by bending up one corner of it. By means of the small compass-needle which you have just been using, proceed to find whether the "tin" is magnetized or not. If it is magnetized, determine whether the marked end is a north pole or a south pole.

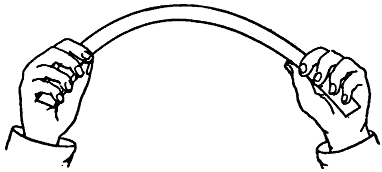

FIG. 80. — Magnetizing a piece of "tin" by bending it in the earth's field.

Having done this, hold the strip by its ends in a vertical position, *with its south pole down,* and bend the strips to and fro two or three times. Again examine the strip with the compass-needle. Is the marked end now a north or a south pole? What has produced the change? If the strip of tin does not show any poles when first examined, that is, if each end produces the same effect upon the compass-needle, hold the marked end down and see what effect the bending has upon it.

(d) Next hold the strip horizontal, in an east and west direction. Having bent it to and fro, while holding it east and west, now examine it with the compass-needle. What effect do you observe? How do you explain this effect? In your report distinguish carefully between a body which possesses *magnetic quality* and one which is *magnetized.*

Exercise 66. — Further Study of a Magnetic Field

References. — CREW, 263; ROWLAND AND AMES, 114; HALL AND BERGEN, 382.

Apparatus. — Bar magnet 2 to 4 inches long; large sheet of white paper; compass-needle, as described in preceding Exercise.

Problem. — To learn a second method of mapping a magnetic field; and also to study the field which is the resultant of the

earth's field, and the field about an ordinary bar magnet. It may be noted that the method used in Exercise 64 (iron filings) is not delicate enough to detect the presence of the earth's field.

Experiment. — (*a*) Lay the sheet of paper on the table with its long edges in a north and south direction. Fasten it in this position with thumb-tacks or small bits of wax. Place the bar magnet in the middle of the paper, with its axis in a north and south line, and its north pole toward the north. With a pencil trace the outline of the magnet on the paper, so that if disturbed it can be replaced.

At some point about a centimetre from the magnet make a dot with a lead pencil. Place the compass-needle so that its end nearest the magnet is directly over the dot. Directly under the other end of the needle make a second dot. Now move the needle so that the first end is over the second dot; and under the second end of the needle make a third dot. Continue this process until the needle either returns to the magnet or reaches the edge of the paper. Connect this series of dots by a continuous line. This will be one of the lines of force of the magnetic field. Now bring the compass-needle back to the magnet and trace another line. In this way map enough lines to give a good idea of the whole field. The starting-points should be taken from $\frac{1}{2}$ cm. to 1 cm. apart, or as close as may be necessary to show the field well.

(*b*) Map in the same way the field obtained by turning the bar magnet end for end, its north pole now pointing south. In the diagram last made, how does the presence of the earth's field show itself? There are certain points in the field at which the magnetic force of the bar magnet is just counterbalanced by the magnetic force of the earth. See if you can find one of these points. You will be surprised to find how closely you can determine its position.

(*c*) If sufficient time remains, map the field produced by placing the axis of the bar magnet east and west: (1) with its north pole toward the east, (2) with its north pole toward the west. How do these two maps compare with each other?

CHAPTER VIII

ELECTROSTATICS

Exercise 67. — Fundamental Experiments in Electrostatics

References. — Crew, 272–277; Rowland and Ames, 116, 118, 119; Hall and Bergen, 386–390; Avery, 324–325; Carhart and Chute, 263–269; Wentworth and Hill, 252, 253, 255, 256; Gage, 281–285.

Apparatus. — A rod of flint glass and one of vulcanite; pieces of silk and flannel for rubbing the rods; electroscope, as in Fig. 81, made of an Erlenmeyer flask with a rubber stopper, through which passes a brass rod carrying two parallel strips of gold or aluminium leaf at the bottom, and either a metal knob or a small metal plate at the top; proof-plane, consisting of a disk of sheet metal about the size of a cent, fastened by wax or by a screw to the end of a vulcanite rod 6 or 8 inches long; gilded pith-ball, suspended by a silk thread; stick of sealing-wax; small camel's-hair brush; dry sponge; feather; bits of tissue paper. (The electroscope appears to hold a charge better if a small piece of caustic soda is placed in it to absorb moisture.)

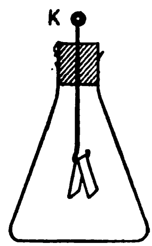

Fig. 81. — Electroscope made from an Erlenmeyer flask and aluminium foil.

Problem. — To examine the kinds of electrification produced by rubbing together different substances, and the forces which electrified bodies exert on each other.

Experiment. — *Preliminary note.* It is essential to success in these experiments that the rods and cloths for rubbing them

be free from moisture. If the rods fail to show a charge when rubbed, both they and the cloths should be dried by sunning them or exposing them to the warm air rising from a radiator. Avoid holding the silk or flannel in the hand when not actually using it. Mark one end of each rod, and handle it only by the marked end.

(*a*) Rub the glass rod with silk, and bring the rubbed end near some small bits of tissue paper, or other light objects. Try this also with a vulcanite rod rubbed with flannel. Describe the result in each case.

(*b*) Suspend a gilded pith-ball by a silk thread. (The coating of gold-leaf makes the ball a good conductor.) Touch the pith-ball with your finger to make sure that it is discharged. Rub a glass rod with silk, and bring it slowly toward the pith-ball. How is the pith-ball affected? Allow the pith-ball to touch the glass rod, thus taking part of the charge from the rod. Now approach the charged ball with the rubbed glass rod. What result? Approach the charged pith-ball with a vulcanite rod rubbed with flannel. What result? Evidently the charge on glass rubbed with silk is different from that on vulcanite rubbed with flannel. Glass rubbed with silk is said to be **positively** electrified; vulcanite rubbed with flannel is **negatively** electrified.

Discharge the pith-ball, and charge it from a vulcanite rod rubbed with flannel. Observe the effect on it of (1) a vulcanite rod rubbed with flannel, (2) a glass rod rubbed with silk. How do two bodies act on each other when they have like charges? When they have unlike charges? How does a charged body act on an uncharged body?

(*c*) Hold the proof-plane by the end of the handle, and touch its metal disk first to a glass rod rubbed with silk, then to the top of the electroscope. By this process a part of the charge is carried from the rod and given to the electroscope. If the charge so obtained is not sufficient to affect the electroscope, draw the proof-plane along the rod, and so collect the charge from a number of points on the rod. What is the effect on

the leaves of the electroscope? Which kind of charge has the electroscope? Touch your finger to the top of the electroscope. This discharges it, that is, allows the charge to escape. Now try the effect of a negative charge on the leaves. What result? Explain how the electroscope is used to determine whether a body is charged or not.

(*d*) Charge the electroscope positively. What is now the effect of touching it (or approaching it) with a positive charge? With a negative charge? Explain how the electroscope may be used to determine *which kind* of charge an electrified body has. Hold your hand or any other uncharged conductor near but not touching the electroscope. Note that this always makes the divergence of the gold leaves slightly diminish. Hence increase of divergence is the only test which is always reliable for the presence of a charge.

(*e*) Determine the kind of electrification on each of the following substances:—

Sealing-wax rubbed (1) with flannel; (2) with silk.

Camel's-hair pencil rubbed (1) on a varnished table top; (2) on your hair.

Dry sponge rubbed (1) on flannel; (2) on your hair.

Eraser on the end of a lead pencil, rubbed on paper.

Feather rubbed on flannel.

Exercise 68. — Conductors and Non-conductors

References. — CREW, 274; ROWLAND AND AMES, 117; HALL AND BERGEN, 389; WENTWORTH AND HILL, 254; CARHART AND CHUTE, 271; GAGE, 286; AVERY, 326.

Apparatus. — Electroscope, as in the preceding exercise; proof-plane; rod of vulcanite; flannel; a foot each of copper, brass, and iron wire; cotton and silk thread; rubber band; glass rod; short rod of dry, unvarnished wood (any piece of ordinary dry pine will do); strip of paper about a foot long; small pieces of paraffin, sulphur, sealing-wax, rosin, celluloid; small tin vessel or glass beaker; alcohol, water, kerosene.

Problem. — To test specimens of various solid and liquid substances, as to their ability to conduct electric charges.

Experiment. — (*a*) Charge the electroscope with the vulcanite rod and proof-plane, as in the preceding exercise. Touch your finger to the top of the electroscope. This discharges the electroscope, the charge escaping through your body. Substances which allow electric charges to escape through them are called **conductors**; those which do not are called non-conductors, or **insulators.**

(*b*) Test copper, iron, and brass wires, and threads of cotton, silk, and rubber, to see whether they are conductors. The wires may be tried by holding one end in the hand, and touching the other end to the charged electroscope. Record the results of all your tests. To test a thread, hold its ends in your two hands, and lightly press its middle part against the top of the electroscope. First test a cotton thread dry, then moisten it by drawing it between your finger and thumb, previously moistened, and test again. Do the same with a silk thread.

(*c*) Test specimens of glass, porcelain, dry wood, sulphur, sealing-wax, rosin, paraffin, celluloid. Do this by holding each piece by one end, and touching the other to the electroscope.

(*d*) In order to test the conducting power of liquids, attach a short copper wire to the top of the electroscope. The wire should extend 4 or 5 inches horizontally, and then vertically downward about 2 inches. Fill a small tin or glass vessel with the liquid to be tested. Charge the electroscope, and, holding the vessel in one hand, raise it until the end of the wire dips into the liquid *without touching the vessel.* If a non-conducting vessel is used, the tip of one of your fingers must also be allowed to touch the liquid. Test in this way water, alcohol, and kerosene.

(*e*) Explain why the leaves of the electroscope are attached to a metal rod. Why is this rod supported on glass?

Arrange all the substances which you have tested in this exercise in three lists, under the headings: "Good Conductors," "Poor Conductors," "Insulators."

Exercise 69. — Electrostatic Induction

References. — CREW, 280, 281; ROWLAND AND AMES, 121; HALL AND BERGEN, 391; CARHART AND CHUTE, 273–276; WENTWORTH AND HILL, 257; GAGE, 287–288; AVERY, 340.

Apparatus. — A rod of metal some 8 or 10 inches in length; a piece of silk thread about 3 feet long; an ebonite rod, preferably about 2 feet long, and a piece of flannel with which to rub it; proof-plane; electroscope; some form of retort-stand or wood clamp.

Problem. — To study a method for producing electrification without the use of friction.

Experiment. — (*a*) Take some long-shaped conductor, such as a brass rod or steel scale, and support it by a silk thread as indicated in Fig. 82, where *M* is the metal rod, and *S* the silk thread. Charge an ebonite rod by rubbing. What kind of electrification is produced on ebonite when it is rubbed with flannel? Positive or negative? What kind of electrification is produced on glass when it is rubbed with silk? By means of a proof-plane, charge the leaves of an electroscope from the charge on the ebonite rod. Do the leaves of the electroscope diverge in consequence of being charged *positively* or *negatively?*

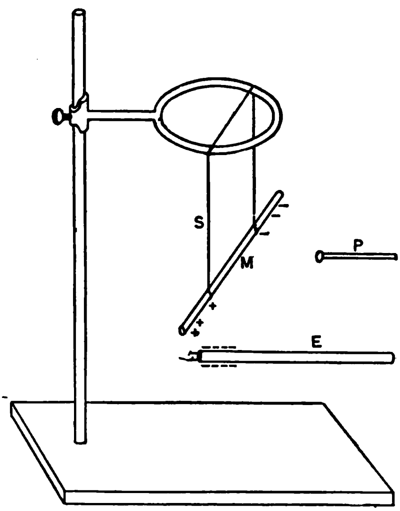

FIG. 82. — Simple device for showing electrostatic induction.

(*b*) While the leaves of the electroscope still diverge, owing to the charge which you have just given them, hold the charged

ebonite rod E near one end of the suspended metal rod M, say within an inch or two of it. While you still hold the ebonite rod near M, proceed to examine the metal by means of the proof-plane. What kind of electrification do you find *on the end next to the ebonite rod?* Is this the same as or opposite to that which you found on the ebonite rod itself? Next find what kind of electrification there is *on the end of the metal farthest away from the ebonite rod.*

In your report, make a diagram showing just what kind of electrification you have

(1) On the rod of ebonite.
(2) On the end of the metal nearest to the charged ebonite.
(3) On the end of the metal farthest from the charged ebonite.

(*c*) Now hold the *charged* ebonite rod near the *other* end of the suspended metal, and again examine the electrification on the two ends of the metal. Does the electrification on the metal change as you carry the charged ebonite from one end to the other?

(*d*) Place the *charged* ebonite rod in a clamp, or on a block, near the suspended metal as before. Now touch the metal rod with one finger for an instant, and then proceed to examine the electrification on each end of the metal rod both before and after withdrawing the ebonite rod. You find it electrified in a manner very different from that of the two preceding cases. Make a diagram showing just what you do find. How do you explain this?

You are now in a position to explain why almost any light body, such as a small piece of tissue paper, or a bit of cotton thread, is attracted by an electrified body. Make a diagram showing just how this attraction occurs. The light body in this case corresponds to the metal bar in the experiments above.

(*e*) Bring the *charged* ebonite rod near the electroscope, not so near, however, as to tear or injure the leaves. With what kind of electrification do the leaves of the electroscope diverge?

How may you charge an electroscope permanently without connecting it to the charged body, and without bringing any conductor into contact with the charged body?

When you bring up the charged ebonite to the electroscope and then take the ebonite away without touching the electroscope, do you find any charge remaining on the electroscope? What may you infer, therefore, as to whether the two charges thus induced on the electroscope are equal or unequal?

Exercise 70. — Further Study of Electrification by Induction — Faraday's Ice Pail Experiment

References. — Crew, 283–285; Rowland and Ames, 121; Carhart and Chute, 270.

Apparatus. — A tin can holding about one pint; a block of paraffin on which to place this tin can; an electroscope; a proof-plane; a piece of flannel about 1 foot square; a rod of hard rubber from 6 to 10 inches long; a cylinder of wire screen large enough to enclose electroscope, as indicated in Fig. 84; a metal sphere an inch or so in diameter provided with a silk thread to suspend it by.

Problem. — To illustrate the fact that whenever electrification is produced, the positive and negative charges so produced are equal; also to illustrate the fact that a closed metallic conductor divides all space into two parts, one of which is not affected by any electrical operations carried on in the other.

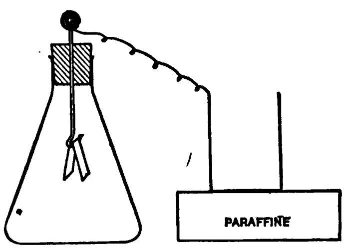

Fig. 83. — **Faraday's ice pail experiment.**

Experiment. — (*a*) Place a tin can on a block of paraffin as indicated in Fig. 83. Line the inside of the tin can with a small roll of flannel, and then connect the can to an electroscope by means of an easily flexible wire. Take an ebonite rod and see that it is not electrified. (You can test

its electrification by bringing it near the electroscope. If it happens to be electrified, discharge it by rubbing your hand slowly over its surface, or by passing it quickly through a Bunsen flame.) Now rub the flannel lining of the tin can with the ebonite rod. What effect is produced on the electroscope when you remove the ebonite rod? When you replace the ebonite rod in the can, what effect do you observe upon the leaves of the electroscope? What may you, therefore, infer concerning the amount of charge on the flannel as compared with that on the ebonite?

(*b*) Remove the flannel from the can, and having discharged the can and all, introduce into the can a charged metal sphere suspended by means of a silk thread about one foot long. As you move the charged sphere about from one place to another inside the can, what effect is produced upon the leaves of the electroscope? Touch the charged sphere to the inside of the can, and observe the effect produced upon the electroscope. How does the amount of the charge on the sphere compare, therefore, with the amount of the charge induced on the inside of the can?

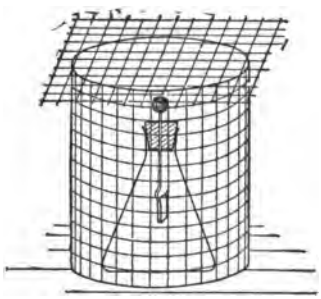

Fig. 84. — Showing how a closed network of wires protects the space within from electrical disturbances without.

(*c*) Place the entire electroscope inside a cylinder of wire netting and see that the top of the cylinder is also covered with wire netting. Bring near the electroscope a heavily charged body such as the rod of ebonite or the "lid" of an electrophorus. What effect is produced upon the electroscope?

CHAPTER IX

ELECTRIC CURRENTS

Exercise 71. — The Galvanoscope — Movable Coil Type

References. — CREW, 290–291; CARHART AND CHUTE, 360; AVERY, p. 527; WENTWORTH AND HILL, 280.

Apparatus. — A voltaic cell, preferably an ordinary dry cell; a U-magnet, mounted on a wooden block, as indicated in Fig. 85; ten or fifteen turns of insulated wire (about $\frac{1}{2}$ mm. in diameter) wound in a flat coil so as to swing freely between the poles of the U-magnet; two insulated wires, each about 3 feet long and $\frac{1}{6}$ mm. in diameter, by which to suspend the above coil; a spring key; a laboratory stand or some other means of suspending the coil, as indicated in Fig. 86. Strong U-magnets of the type indicated above can be obtained from Richards & Company, 108 Lake Street, Chicago, for fifty cents each.

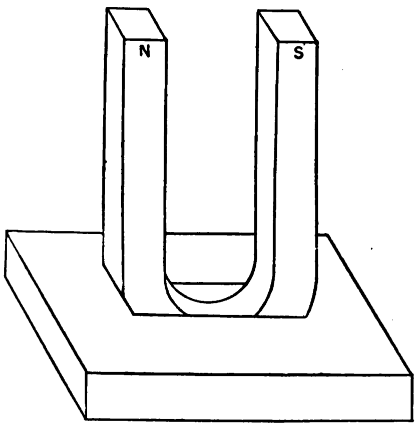

FIG. 85. — U-magnet employed to furnish the "field" for a D'Arsonval galvanometer.

Problem. — To study a method for detecting the presence of an electric current in a wire; in particular to explain the principle of the D'Arsonval galvanometer.

Experiment. — (*a*) Take a U-magnet which is mounted in a block so that it will stand upright, as indicated in Fig. 85. Estimate roughly the height of the top of the magnet above the top of the table upon which you are working. Approximately at this same height suspend a small flat coil of rather small insulated copper wire so that the coil can turn easily about a vertical axis. The best way of doing this is, perhaps, to suspend the coil from a stand (or wall bracket) by means of two finer insulated wires which lead away from the coil, as indicated in Fig. 86. One of these finer supporting wires should be straight and carry the weight of the coil, while the other is twisted loosely about it.

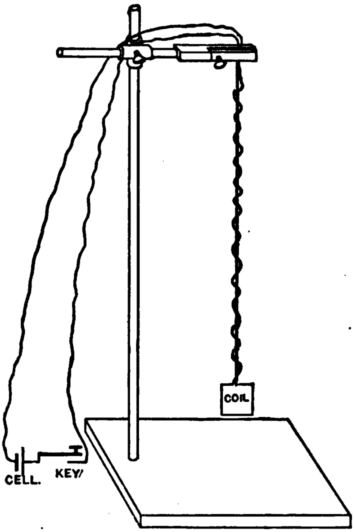

FIG. 86. — Galvanoscope coil, capable of rotating about a vertical axis; form used by D'Arsonval.

Next join the two terminals of a voltaic cell to the two ends of the suspended wire, having placed in the circuit a spring key, so that you can start and stop the current at will. On closing the circuit you will probably observe no effect, or at most a very slight rotation of the coil.

(*b*) Now bring up the U-magnet so that the suspended coil hangs exactly between the poles of the magnet when the key is not closed. On pressing down the key, that is, on starting the current, you will observe that the coil now rotates through a considerable angle.

Place the magnet in a number of different positions with respect to the suspended coil, and find in which one the rotation of the coil is greatest. In which position of the magnet

is there practically no deflection when you close the key? Remember that the lines of force about a magnet always run from the north to the south pole.

How must the plane of the coil be set with reference to these magnetic lines in order to give a maximum rotation?

(*c*) Having placed the magnet so that its lines of force are parallel to the plane of the coil, and having observed the direction in which the coil rotates when a current is passed through it, turn the magnet round, *without touching the coil,* so that the north and south poles just interchange places. Again close the circuit; how does the rotation of the coil now compare with what it was before?

(*d*) Allowing the magnet and coil to remain in their present position, interchange the connections of the wires at the battery. Again close the circuit. What effect does this change of wires produce upon the rotation of the coil?

(Remember that the direction of the current through the coil is *from the carbon to the zinc pole,* when an ordinary dry cell is used. Likewise, the current of an ordinary gravity cell is said to flow *from the copper to the zinc pole,* through the outside circuit.)

From the above experiments, it is evident that the suspended coil, whenever a current passes through it, behaves very much like a suspended magnet. But when there is no current passing, the behavior of the coil is that of a non-magnetic body. This instrument is admirably adapted, therefore, to detect the presence of electric currents. It has been perfected by the labors of Ampère, Kelvin, Deprez, D'Arsonval, and Rowland.

Exercise 72. — The Galvanoscope — Fixed Coil Type

References. — Crew, 291; Rowland and Ames, 128; Carhart and Chute, 317–318, 339, 358, 359; Hall and Bergen, 412–413; Avery, 375, 414; Wentworth and Hill, 278–281; Gage, 309, 349.

Apparatus. — A copper wire, 1 or 2 feet long, stretched between binding posts, as indicated in Fig. 87; a small compass-needle, mounted on a pivot or suspended by a fibre, preferably the former; a spring key; a battery of two cells. The best arrangement of all is a battery of two or three storage cells with a pair of mains running about the walls of the laboratory and having outlets at each table. One pair of such cells will supply the entire laboratory, provided spring keys are used. In case no other source of current is available, the storage cells may be charged by an ordinary gravity battery. In case storage cells are not available, two ordinary dry cells for each table are convenient and cheap, and answer this purpose very well.

Problem. — To study the magnetic field about a straight wire conveying an electric current; in particular, to discover a

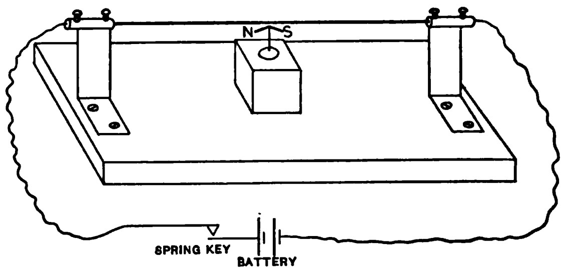

FIG. 87. — Oersted's experiment.

method for detecting the presence of an electric current, and to explain the principle of the ordinary fixed coil galvanometer.

Experiment. — (*a*) Take a wire stretched between two uprights, as shown in Fig. 87. Place this stretched wire in the magnetic meridian, as you can readily do by placing the wire parallel to the direction in which the magnetic needle points. Remember that the magnetic meridian at any point is defined as the direction of the needle at that point. To the ends of

this stretched wire connect the poles of a battery, say two or three dry cells, or a couple of storage cells. Join in the circuit a spring key, as shown in the diagram, so that your battery will not waste its energy except while you are actually using it.

Arrange your circuit so that the current in the stretched wire flows from south to north; in order to do this you have only to connect the south end of the wire with the positive pole of your battery. (In the ordinary dry cell the positive pole is the carbon; in the gravity cell the positive pole is copper; in the storage cell the positive pole will be marked thus, "+.") The problem now is to examine the region round about the wire through which a current is passing. If the current produces a magnetic field about the wire, this field can be detected by a small magnet, as was seen when we were studying the region about iron magnets.

Take a small magnet mounted on a needle point (or suspended by a fibre), and place it on a support so that the little magnet lies just above the wire and very near it, say $\frac{1}{8}$ or $\frac{1}{2}$ inch from it. Be sure that the compass needle is marked in some way so that you know which is the north pole and which the south.

(*b*) Now press down the key and proceed to answer by experiment the following questions:

CURRENT FLOWING FROM SOUTH TO NORTH

Position of Magnet	*North Pole*
Above wire . .	deflected toward east or west?
Below wire . .	deflected toward east or west?
East of wire . .	lifted up or pushed down?
West of wire . .	lifted up or pushed down?

From these observations, what appears to be the direction of the lines of force about the wire? Could they be repre-

sented by circles drawn about the current, as shown in Fig. 88? Place an arrow on each of the circles indicating the direction of the line of force when the current has the direction given in the diagram. Remember that the direction of the line of force at any point is the direction in which a free north pole would move at that point.

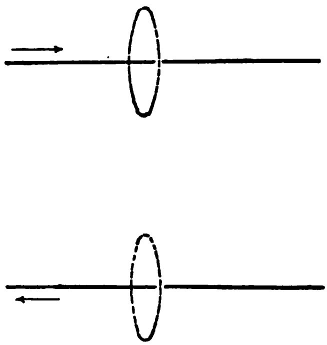

Fig. 88.—Illustrating direction of lines of force about a current; diagram to be completed by the student.

(*c*) Now interchange the ends of the circuit which are connected with the battery, so that the current in the stretched wire flows *from north to south,* and then proceed to make the following observations:

Current flowing from North to South

Position of Magnet	*North Pole*
Above wire . . .	deflected to east or west?
Below wire . . .	deflected to east or west?
East of wire . . .	lifted up or pushed down?
West of wire. . .	lifted up or pushed down?

From these observations would it be allowable to infer that the direction of the magnetic field is reversed when the direction of the current is reversed? Suppose all the rest of the circuit were hidden, could you tell from the behavior of the magnet whether or not a current was passing through the wire?

Exercise 73.—Fundamental Phenomena of the Voltaic Cell

References.—Crew, 295–298; Rowland and Ames, 126; Hall and Bergen, 402; Avery, 346–349; Wentworth and Hill, 271: Carhart and Chute, 314–329; Gage, 297–305.

Apparatus. — A U-tube mounted on a block and provided with binding-posts as indicated in Fig. 89. The arms of this tube need not be over 3 or 4 inches long, with an internal diameter of $\frac{1}{4}$ to $\frac{1}{2}$ inch. A galvanometer sensitive enough to give considerable deflection for zinc and copper plates in sulphuric acid. From twelve to fifteen dollars will purchase an excellent D'Arsonval galvanometer and scale. A galvanometer of this type, *provided its resistance does not exceed five ohms*, will excellently serve all the purposes of this course, and will answer also for demonstrations in the classroom. Such instruments may be obtained from the Chicago Laboratory Supply and Scale Company, and from William Gaertner & Company, 5347 Lake Avenue, Chicago, from Richards & Company, and from various other firms. A spring key; two narrow strips of clean sheet copper, and two narrow strips of clean sheet zinc, just large enough to fit into the U-tube above mentioned; commutator.

Problem. — To study the method, devised by Volta, for producing electric currents; namely, the method in which are employed two "conductors of the first class" and one "conductor of the second class"; also to explain the construction of a commutator.

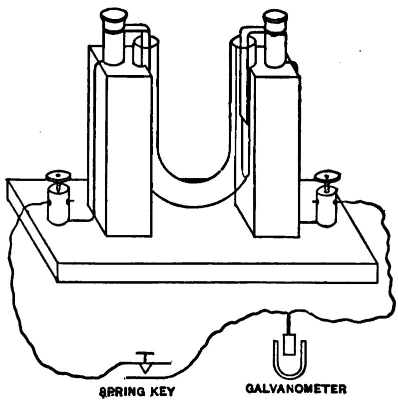

Fig. 89. — A convenient arrangement for studying the action of the Voltaic cell.

Experiment. — (*a*) Take two *clean* copper strips or wires and place one in each arm of a small U-tube filled with dilute sulphuric acid. A very convenient arrangement of the U-tube is that indicated in Fig. 89.

Next arrange your circuit as shown in the diagram, placing

a spring key "in series" between the U-tube and the galvanometer. If you do not know what "in series" means, ask your instructor before going any farther with this work.

The galvanometer which you will use is merely a modification of one of the two forms described in the two preceding exercises. On pressing down the key you will find that the two copper strips in sulphuric acid produce little or no current. The reason for this is that the two electrodes in the acid are each made of the same metal; and there is no ground for expecting the current to flow in one direction rather than the other.

(*b*) Now remove both the copper strips from the U-tube and replace them by two *clean* strips of zinc. On again pressing down the key, you will observe practically no current; for as in the preceding case, the electrodes are exactly alike, and there is no reason why a current should flow in one direction rather than in the other. If the galvanometer should indicate a small current, it is probably due to the fact that the two pieces of zinc are not *exactly* alike.

(*c*) But now replace only *one* of the zinc strips with a *clean* copper strip. The circuit is now made up of sulphuric acid, zinc, and copper. On closing the key you find a considerable deflection of the galvanometer, which indicates that there is a considerable current flowing through the circuit. And you will find that this current persists until the zinc is "eaten up" by the sulphuric acid. This is a typical voltaic cell. The direction of the current is said to be from the copper strip through the galvanometer to the zinc strip; for this is the direction in which positive electrification is carried. If you had used a solution of zinc sulphate in one arm of your tube and a solution of copper sulphate in the other, you would have had a "gravity cell." If you had used a carbon electrode instead of copper, and ammonium chloride instead of sulphuric acid, you would have had a "Leclanché cell."

What is the source of energy which furnishes the electric current in each of these cases? When zinc is "eaten up," or

as the chemist would say "oxidized," in the sulphuric acid, it is burned up just as truly as carbon is burned up in a stove.

(*d*) Now introduce into your circuit a commutator as indicated in Fig. 90. You can now change the direction of the current through the galvanometer. In your report *make a diagram of this commutator*, showing just how by use of it you can interchange the connections between the battery and the galvanometer.

Report the deflections which you get before and after reversing the current by use of the commutator.

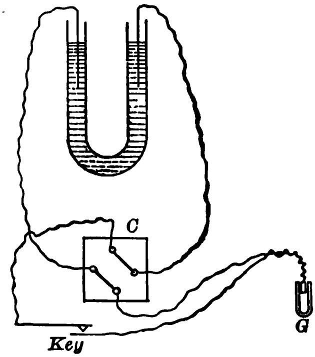

Fig. 90. — Illustrating the use of the commutator.

Exercise 74. — Electromagnetic Induction

References. — Crew, 299–302; Rowland and Ames, 134; Hall and Bergen, 436–437; Carhart and Chute, 366; Avery, 388; Wentworth and Hill, 313; Gage, 364.

Apparatus. — Sensitive galvanometer, preferably one of the D'Arsonval type; horseshoe magnet; straight bar magnet; coil of wire some 6 or 8 inches in diameter, and having a number of turns sufficient to give a distinct throw of the galvanometer when the coil is quickly turned over in the earth's field; two wire connectors, and a pair of long "leads" for the galvanometer.

Problem. — To study a most important method of producing electric currents, namely, that discovered by Faraday in 1831. This experiment is intended to illustrate the fundamental principle upon which the dynamo and the telephone receiver are constructed.

Experiment. — (*a*) Join a coil of wire to the terminals of your galvanometer without putting any battery in the circuit,

so that the entire circuit may be considered a single copper wire without any source of current in it.

Before performing the remainder of this experiment it is essential that your ideas concerning the lines of force about an ordinary bar magnet should be clear. Remember that these lines leave the north pole, pass around, and enter the magnet at the south pole. When you pick the magnet up and carry it about, these lines of force go with it as if they were rigidly attached to it.

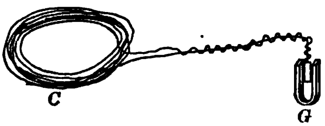

FIG. 91.—Circuit arranged to show the phenomena of induced currents.

(b) Next determine which end of your magnet is the north pole and which the south. If the poles are not already marked in some way, paste a bit of paper on the north pole so that you can easily distinguish it.

(c) Now hold the magnet by the south end, and quickly bring the north end near the centre of the coil of wire, as shown in Fig. 92. By this operation do you increase or diminish the total number of lines of force passing through the coil? Does your galvanometer show any current while the magnet is approaching the coil? Does the galvanometer show any current while the magnet is being taken away from the coil? How do the directions of these two currents compare?

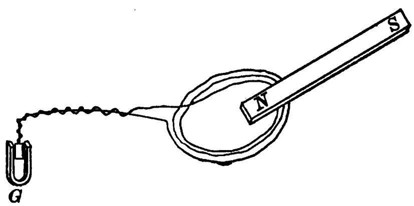

FIG. 92.—Simple method of thrusting magnetic lines of force through a circuit, thereby inducing an electric current.

Now allow the magnet to remain at rest with one end in the coil, as shown in Fig. 92. Does the galvanometer indicate any current in the coil while the magnet is at rest?

(d) Next allow the magnet to remain at rest with one end projecting over the table as indicated in Fig. 93. Take the

coil in your hand, and quickly thrust the coil over the end of the magnet, but without touching the magnet. Do you observe any deflection of the galvanometer? By moving the coil in this way do you alter the total number of lines of force passing through the circuit?

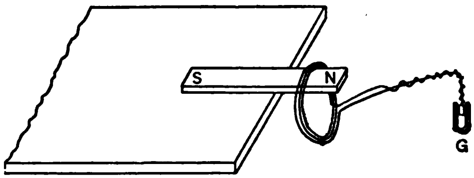

FIG. 93.—Showing that motion of either coil or magnet with reference to the other induces a current.

(*e*) Now reverse the ends of the magnet, allowing the opposite pole to project over the table; and, after the galvanometer has come to rest, again slip the coil over the end of the magnet, but without touching the magnet. You observe a current. How does the direction of this current compare with that of the current just previously obtained? Do the lines of force now run through the coil in the same direction as before, or in the opposite direction?

(*f*) You remember that all the region about the surface of the earth is a magnetic field, that is, the region is filled with magnetic lines of force. Hold the coil of wire in position where you think it will include the greatest possible number of these lines of force; and when the galvanometer needle is at rest, quickly turn the coil into a position where the number of the earth's lines of force passing through it will be as small as possible. If you have correctly chosen the positions, you will probably observe a minute deflection of the galvanometer.

(*g*) Now place the coil flat on the table, and when the galvanometer is at rest quickly turn the coil over. You observe a small deflection. How do you explain this in the light of the preceding experiments?

(*h*) Hold a horseshoe magnet upright on the table and slip the coil over *both* its poles. Note the deflection. Now slip the coil over *only one* pole of the horseshoe magnet. The

deflection is very different from the preceding. How do you explain this?

Exercise 75. — Induction of Electric Currents

References. — Crew, 301–304; Rowland and Ames, 134; Avery, 389–402; Wentworth and Hill, 327; Gage, 356–358; Carhart and Chute, 367–370.

Apparatus. — About 100 feet of annunciator wire, wound into two flat coils, each coil being 4 to 6 inches in diameter, and containing about 50 feet of wire — about 2 feet of each end of the wire should be left free for "leads"; one or two cells of dry battery; spring key; galvanometer, sufficiently sensitive to give a deflection of at least one or two scale divisions, when one of the above coils is "capsized" in the earth's field.

Problem. — To study another method of changing the number of lines of force passing through a circuit; that is, to produce induced currents in one circuit by varying the current in a neighboring circuit.

Experiment. — (*a*) Connect the ends of one of the coils of wire to the poles of the battery, and *place a spring key in the circuit.* The ends of the other coil are to be connected to the galvanometer terminals. We thus have two entirely independent circuits. The coil connected to the battery is called the **primary** coil. The coil in the same circuit with the galvanometer is called the **secondary** coil. Lay the secondary coil flat on the table, and place the primary coil on top of it. Now, with your eye at the galvanometer, press down the key and keep it down. Note the amount and direction of the galvanometer deflection. Is the current in the secondary a permanent or a temporary one? Is the secondary current the result of a

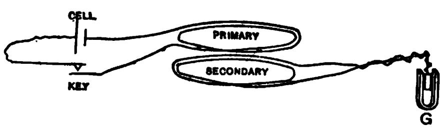

Fig. 94. — Thrusting lines of force through a secondary circuit, by varying the current in a primary circuit.

steady current in the primary, or the result of a varying one? What effect do you observe on opening the key? How do the deflections compare on opening and on closing the key?

(*b*) Reverse the battery connections, and find whether the deflection on closing the circuit is the same as it was before.

(*c*) Now, leaving the secondary coil undisturbed, lift up the primary coil, turn it over, and replace it upon the secondary. Again close the circuit, and note the direction of the galvanometer throw. Is this direction the same as before you reversed the coil?

(*d*) Close the key, and keep it closed until the galvanometer returns to zero. Now, with the primary current flowing steadily, quickly lift the primary coil from the secondary, and carry it a foot or more away. What happens in the secondary circuit? With the key still closed, and after the galvanometer has come to rest, bring the primary quickly back to the secondary. What result? Is the current induced by removing the primary in the same direction as that induced by bringing it back?

(*e*) Allow the key to remain open, and find whether any effect is produced in the secondary circuit by removing the primary coil when no current is flowing in it.

Exercise 76. — Thermo-electric Currents

References. — Crew, 306; Rowland and Ames, 127; Wentworth and Hill, 305; Gage, 372–373; Avery, 411.

Apparatus. — A foot each of copper, iron, brass, and german silver wire, about 0.5 mm. in diameter; galvanometer, preferably of the D'Arsonval type,— any low resistance galvanometer, sensitive enough to show thermal effects, will answer; tin cup of water, arranged over a Bunsen burner so that the water may be boiled; "lead" wires for galvanometer.

Problem. — To study a method of producing electric currents directly from heat.

Experiment. — (*a*) Connect the ends of the wires leading to the galvanometer terminals by a short piece of iron wire, as in Fig. 95, twisting the wires together so as to make firm joints. So long as the two junctions of iron and copper are at the same temperature no current will flow, and the galvanometer will not be deflected. (See Crew's *Elements of Physics*, Art. 293.) Warm one of the junctions, say the right-hand one, by holding it between your thumb and finger. Note the amount of the galvanometer deflection, and also the direction, whether to the right or to the left.

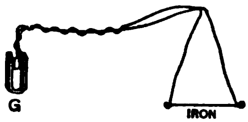

Fig. 95. — **Circuit arranged to show the production of an electric current directly from heat.**

Now let the warm junction cool, so that the reading of the galvanometer will return to zero; and then warm the left-hand junction in the same manner. Does the current flow in the same direction as before? Evidently the direction of the current depends on which junction is at the higher temperature. It has been found that when copper and iron are used, *the current flows across the hot junction from copper to iron.*

(*b*) Heat one of the copper-iron junctions by plunging it into *boiling* water. When the galvanometer has settled, record the scale reading. This deflection may be taken as a measure of the amount of current flowing, when one of the copper-iron junctions is kept at 100° C., and the other at the temperature of the room.

(*c*) Now replace the iron wire by a brass wire. Determine, by comparison with the copper-iron circuit, (1) which way the current flows across the hot copper-brass junction — whether from copper to brass, or from brass to copper; (2) whether the same difference of temperature between the two junctions sets up a larger current in a copper-brass circuit or in a copper-iron circuit.

(*d*) Replace the brass wire by one of german silver. Find, as above, the direction of the current across the hot junction,

and the relative amount of current set up when one junction is heated to 100° C.

(*e*) Finally, replace the german silver wire by a copper wire. You will now find that heating one of the junctions does not set up an appreciable current in the circuit. Indeed, we should not expect a current in this case, for, since both of the wires at a junction are of the same metal, there is no reason why a current should flow in one direction rather than in the other.

Thermo-electric junctions, similar to those you have been using, are frequently employed for measuring temperatures. Of the pairs of metals you have examined, which would you select as being the most sensitive for this purpose?

Exercise 77. — Electrolysis

References. — Crew, 307; Rowland and Ames, 130; Hall and Bergen, 404–405; Avery, 429; Carhart and Chute, 332–337; Wentworth and Hill, 306–312.

Apparatus. — Battery, preferably of two or three storage cells, three or four cells of dry battery may be used if preferred; water, acidulated with sulphuric acid; solution of copper sulphate; 4 inches of platinum wire; clean bright wire nail; copper wire for making connections; small beaker, holding, say, 1 ounce.

Problem. — To show that solutions are decomposed when a current is passed through them.

Experiment. — (*a*) To each pole of the battery connect a piece of copper wire 2 or 3 feet long. To the free end of each of these wires attach about 2 inches of platinum wire. Dip the two platinum terminals in a small beaker of water, to which a little sulphuric acid has been added. Do not let the copper wires touch the water. Bubbles of gas will be seen to form at each of the platinum electrodes. The gas which appears at the **anode** (the wire by which the current enters the solution) is oxygen; the gas appearing at the **cathode** (the wire by which the current leaves the solution) is hydrogen. Thus

the current has decomposed part of the water into its two constituent gases. In this experiment, platinum wires are used because they are not affected by sulphuric acid, the solution which we are using, or by its decomposition products.

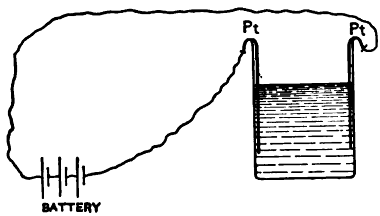

Fig. 96. — Circuit arranged for studying the chemical effects of an electric current.

(*b*) Take off the platinum terminals, and allow the ends of the copper wires to dip into the acidulated water. You will now see that the effects of the currents are quite different from those observed with platinum poles. Gas is now evolved only at the cathode. Watch the anode closely, and you will see that the solution in its neighborhood is becoming tinged with a blue color. In the course of a few minutes you will notice that the copper anode has become brighter, while the appearance of the cathode is little changed.

The sulphuric acid is here being decomposed by the current. One of its components, hydrogen, appears in bubbles at the cathode. The other component is set free at the anode, and immediately unites with some of the copper, forming copper sulphate. This diffuses through the water near the anode, coloring it blue. The outer layer of metal being removed by the action of the acid, the surface of the anode appears clean and bright.

(*c*) Next dip the copper electrodes into a solution of copper sulphate. No gas will now appear at *either* pole (unless too strong a current is used). Both electrodes here change in appearance. The current is now decomposing the copper sulphate. One of the components is metallic copper, which appears at the cathode, and is deposited upon it, so that the cathode soon becomes changed in appearance by the new layer of copper formed on it. The other component of the copper

anode, and immediately unites with
there. New copper sulphate is thus
which has been decomposed. The
unchanged in composition, while cop-
ode and deposited upon the cathode.
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ail soon becomes coated with a film
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f copper is more easily seen on the
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ithin the cell itself.

Exercise 75. — Further Study of Electrolysis

References. — Crew, 307; Rowland and Ames, 130; Hall and Bergen, 404–405; Gage, 307; Carhart and Chute, 332–337; Wentworth and Hill, 306–312.

Apparatus. — Battery, consisting of two or three storage cells, or three or four dry cells, — the latter will answer perfectly; two platinum electrodes, each made by soldering a piece of platinum wire 2 inches long to the end of a short flexible copper wire; small glass beaker, holding 1 or 2 ounces; solution of potassium iodide, to which a little starch paste has been added; solution of table salt; acid solution of lead acetate; small piece of filter paper; solution of phenol-phthaleïn; small piece of window glass.

Problem. — A further study of the decomposition of chemical compounds by the electric current.

Experiment. — (*a*) Attach the platinum electrodes to the poles of your battery as indicated in the figure by means of the

copper wires to which they are soldered. Dip the platinum electrodes into a small beaker containing a solution of potassium iodide, to which a little starch paste has been added. What changes, if any, do you notice in the solution? What do you observe at the anode? At the cathode? It is a well-known fact that free iodine causes starch to turn blue. Indeed, this is a common test for the presence of free iodine in a solution. What, then, is probably one of the products of the decomposition of potassium iodide by the current?

(*b*) To about half an ounce of a solution of common salt (sodium chloride) add a few drops of a solution of phenol-phthaleïn. Lay a small piece of filter paper on glass and saturate it with the solution. (See Fig. 97.) Bring the tips of the platinum electrodes into contact with the wet paper, at two points close together, and slowly move them apart along the paper.

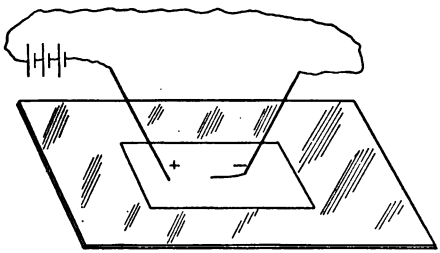

FIG. 97.—Chemical effect of electric current indicated by change of color.

What change do you notice? Does this change occur at the anode, or cathode, or both? Phenol-phthaleïn is much used by chemists as a test for the presence of alkaline substances, as it turns red in their presence. When a salt of sodium is decomposed in this manner, one of the products of decomposition is the metal sodium. This unites with part of the water and forms caustic soda, which is strongly alkaline. At which electrode is the caustic soda formed?

(*c*) Immerse the platinum electrodes in a solution of lead acetate, contained in a small beaker. The solution will be decomposed, metallic lead appearing at the cathode, where it gathers in crystalline masses. This is sometimes called the "lead tree." Repeat this experiment with the battery poles

reversed. Judging from the preceding experiments, at which electrode would you expect metals, in general, to be deposited?

Exercise 79. — Heating Effect of an Electric Current

References. — Crew, 310, 311; Rowland and Ames, 129; Avery, 362–363; Carhart and Chute, 330–331; Wentworth and Hill, 298–299, 302–303; Gage, 311.

Apparatus. — Three cells of storage battery, or, if these are not available, three bichromate cells may be used; the cells in either case are to be joined in series, and from each pole of the battery thus formed, a wire should lead to the experimenter's table; two wire connectors; the lead (graphite) from an old pencil, obtained by boiling the pencil until it falls apart; a foot each of No. 36 iron and No. 36 copper wire; old flat file.

Problem. — To show that when an electric current flows through any conductor, heat is generated in the conductor.

Experiment. — (*a*) Attach an old flat file to one of the battery wires, by winding the wire two or three times around the file. Draw the end of the other wire quickly along the rough surface of the file. (If the battery is of a kind likely to be injured by short-circuiting, a suitable resistance must be placed in the circuit.) Sparks will usually be formed at the points where the wire touches the file. These are caused by the heating up of the metal of the file, or of the wire, or both, small particles of which are heated by the current sufficiently to burn or to vaporize them.

(*b*) Fasten a foot of No. 36 copper wire to a foot of No. 36 iron wire, by twisting their ends together, so as to form a single wire about two feet long. Support this wire horizontally, by fastening its free ends to two supports, such as the uprights of two retort-stands, or the tops of two nails driven into a board. Taking a battery wire in each hand, touch one of these to the fine iron wire, and the other to the fine copper wire, each point of contact being about six inches from the twisted junction. Allow the current to flow for a few seconds, and record

the effect on the fine wires, if you notice any. If no change is seen, make two new points of contact about an inch nearer the junction, and so continue to use shorter and shorter lengths of the fine wire, until some effect of the current becomes evident. Describe this effect.

In which wire is the greater amount of heat generated, the copper or the iron? Is this due to a stronger current in one than in the other, or do both carry the same current? Which of the wires has the greater resistance, the copper, or the iron? If you do not know, consult a table of resistances. Does an increase of resistance increase or diminish the amount of heat generated by a given current?

(*c*) Interchange the two battery wires in your hands, so that the current is sent through the fine wires in the opposite direction. Does the direction of the current have anything to do with deciding which of the two wires becomes hotter?

The action of the common incandescent lamp depends simply upon the intense heating of a fine carbon wire of high resistance, by the passage of a current through it. The wire is prevented from burning up by exhausting the air from around it, so that the carbon cannot oxidize.

(*d*) To the end of each battery wire fasten a short piece of graphite from a lead pencil. Bring the ends of these carbons into contact for an instant, and then separate them by a small fraction of a millimetre. A small amount of carbon will be sufficiently heated to vaporize, and the carbon vapor will act as a conductor, carrying the current from one pole to another, even when they are not quite touching. On this principle depends the working of the ordinary arc light.

Exercise 80. — Magnetic Field surrounding a Coil of Wire carrying a Current

References. — Crew, 315; Rowland and Ames, 128; Carhart and Chute, 317, 341, 342, 344; Wentworth and Hill, 282; Gage, 350–352; Avery, 375.

Apparatus. — Glass tube about six inches long and one inch in diameter; about ten feet of insulated copper wire — ordinary annunciator wire is suitable; battery of one cell — a dry battery is very convenient; spring key; commutator; a number of pieces of soft iron wire, of about the length of the tube; small magnet, mounted on a needle point, as in Fig. 98; two lengths of wire for joining the coil to the battery.

Problem. — To study the magnetic field surrounding a coil of wire in which a current is flowing; and to observe the effect of inserting an iron core.

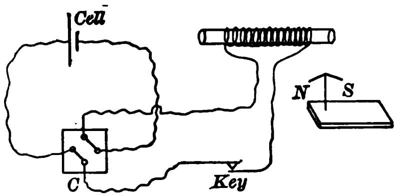

FIG. 98. — Circuit arranged to study the magnetic field produced by a helix carrying a current.

Experiment. — (*a*) Wind 10 feet of covered wire on the outside of a glass tube, in the form of a helix. Join the free ends of the helix to two opposite points of a commutator, inserting a spring key, as shown in Fig. 98. To the other two points of the commutator connect the poles of a voltaic cell. Complete the circuit by pressing down the key. While the current is flowing, present one end of the helix to the compass-needle. How does this end of the helix affect the north pole of the needle? How does the same end affect the south pole? Since the helix acts as a magnet, proceed to determine which is the north pole of the helix, and which is the south pole.

Remember that the current leaves a cell at the carbon or copper pole, and enters it at the zinc pole. As you look through the helix tube, with the north end held toward you, does the current flow round the tube in a clockwise, or in a counter-clockwise direction?

(*b*) Reverse the direction of the current in the helix by means of the commutator. Test the ends of the coil as above. Which end is now the north pole? Holding the north pole of the helix toward you, again determine whether the direction of

the current is clockwise or counter-clockwise. Make a diagram of the helix, showing the direction of the current around it, and the direction of the lines of force through it.

(*c*) Unwind the wire from the glass tube, and rewind it in the opposite direction. Now repeat (*a*) and (*b*), determining for each position of the commutator the direction of the current in the helix when the north pole is held toward you.

(*d*) Introduce into the tube a bundle of soft iron wires. These should first be tested with the compass-needle to see that they are unmagnetized. If they show evidence of magnetization, strike them sharply on the table top, while holding them east and west. Is the magnetic force of the helix more, or less, intense when an iron core is supplied?

Now remove the iron wires, and change them end for end, *leaving the direction of the current unchanged.* Are the poles reversed by this change?

OHM'S LAW

The first simple statement of the manner in which electrical pressures behave, in driving currents through conductors, was given by G. S. Ohm, a German mathematician, in the year 1828. His description is as follows: If, in any single circuit, such as that shown in Fig. 99, where the same kind and size of wire is used throughout, the electrical pressure be measured at various points, it will be found that this pressure varies at a constant rate as we go along the wire. Or, in other words, if we select any two points on the wire, say three inches apart, and if we call the difference of electrical pressure between them e, then so long as we do not change the current in the wire, e will be the difference of electrical pressure, *between any other two points on this wire which are three inches apart.*

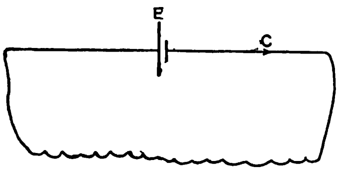

FIG. 99. — Ohm's Law applied to an entire circuit.

If we call the current C, then the ratio $\frac{e}{C}$ is a *constant for*

every three inches of the wire whether the current be changed or not. This constant is called the **resistance** of three inches of this wire. In general, the numerical value of this constant depends upon the size and upon the material of which the wire is composed.

If now we consider an entire circuit, such as that shown in Fig. 99, Ohm's description of it may be written as follows:

$$\frac{\text{Total electrical pressure}}{\text{Current}} = \text{Total resistance of circuit.}$$

This statement is usually known as "Ohm's Law."

If now we denote the total electrical pressure by E and the total resistance of the circuit by R, this law may be written in a very simple form, namely,

$$C = \frac{E}{R}.$$

The unit which is employed by all civilized nations for measuring electrical pressures is the "volt"; in like manner the unit of current is called an "ampere," and the unit of resistance an "ohm." Accordingly, we may put Ohm's Law as follows:

In any electrical circuit, the total electrical pressure in volts, divided by the total resistance in ohms, is numerically equal to the current in amperes.

But it is frequently, indeed generally, necessary to study *only one portion* of an electric circuit at a time; such a portion, say as that between a and b in Fig. 100. And fortunately, Ohm's Law holds in the same way for a portion of a circuit as for the entire circuit, always *provided there is between the points a and b nothing of the nature of a battery or dynamo, that is, no source of electrical pressure.* Ohm's Law for this portion of the circuit would then read as follows:

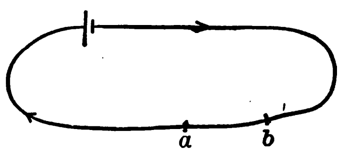

FIG. 100. — Ohm's Law applied to a portion of a circuit.

The difference in electrical pressure, in volts, between the points *a* and *b*, divided by the resistance, in ohms, between the points *a* and *b*, is numerically equal to the current, in amperes, flowing between *a* and *b*.

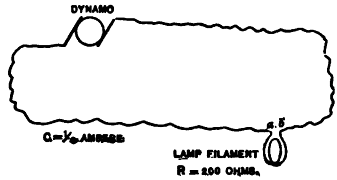

FIG. 101. — A numerical illustration of Ohm's Law.

Thus, if the points *a* and *b* are the terminals of an incandescent lamp whose filament has a resistance of 200 ohms, and if the electrical pressure between *a* and *b* is 100 volts, then the current in the lamp is exactly one-half an ampere.

The following two exercises are intended to make clear the precise meaning of Ohm's Law:

Exercise 81. — Fall of Electrical Pressure along a Wire conveying a Current

References. — CREW, 320–322; ROWLAND AND AMES, 132; HALL AND BERGEN, 419–424; GAGE, 318, 320; AVERY, 355–356.

Apparatus. — A brass, or german silver wire, about 1 metre long, and from $\frac{1}{2}$ to 1 mm. in diameter, stretched on a board and provided with binding-posts at each end, as indicated in Fig. 102; dry cell and resistance (R_1, in figure), sufficient to control current; galvanometer with resistance (R_2, in figure), sufficiently high to render the instrument a voltmeter; commutator. The stretched wire may be clamped to a table, instead of being mounted on a board; but, in either case, it should have a metre scale placed alongside it.

Problem. — To study the manner in which electrical pressure varies from one point to another along a conductor conveying a constant current; in particular, to find how the difference of electrical pressure between two points varies with the length of wire between these same two points, the wire being of uniform cross-section and of uniform material; a partial verification of Ohm's Law.

Experiment. — (*a*) Pass a small battery current through a straight brass or german silver wire. Join up the battery *E* and the commutator, as shown in Fig. 102.

The first problem is to measure the electrical pressure between any two points on this wire. This is done in exactly the same way in which we might measure the difference of pressure between any two points on a water main in the street; namely, we might connect the two points on the water main by a long pipe of very small bore, and then, if there is any difference of pressure between the two points on the main, a current will flow through this small branch pipe.

In like manner we connect the two points *A* and *B* of the circuit which we are about to study by means of a branch circuit *AGB*. Now if there is any difference of electrical pressure between *A* and *B*, a current will pass through *AGB*; and if we include in this branch circuit a galvanometer *G*, we shall have the means of telling, at any instant, whether a current is passing, and just how much current is passing.

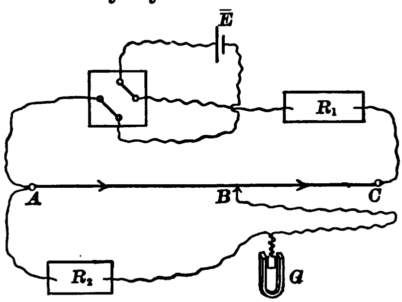

FIG. 102. — Testing the variation of electrical pressure from one point to another along a uniform wire.

(*b*) Having clamped one terminal of the galvanometer at one end, *A*, of the brass wire, move the other terminal along until it is in contact with the other end, *C*, of the brass wire. You have now the largest deflection of the galvanometer which you can obtain by sliding the terminal *B* along the wire. Accordingly, your galvanometer circuit should be adjusted by placing resistance in the circuit,* as indicated at R_2 in Fig. 102, so that the maximum deflection can be easily read on the scale of the galvanometer. Or, if more convenient, you may regulate the

* The instructor may find it more convenient and safer to shunt the galvanometer before the student comes into the laboratory.

N

deflection by varying the current in the stretched wire. But, whichever method you use, the resistance in the galvanometer must be kept high in comparison with the resistance of the stretched wire, else your galvanometer will not measure electrical pressures. See Appendix B.

(*c*) We shall suppose now that you have joined up the circuit in a manner equivalent to that shown in Fig. 102, and that your galvanometer will measure any current you may obtain by fastening one terminal at *A* and sliding the other along the stretched wire. Next, proceed to measure the electrical pressure (galvanometer deflection) between the points "A" and "10 cm." mark, "A" and "20 cm." mark, "A" and "30 cm." mark, etc., throughout the entire length of the scale. This you can readily do by moving the terminal *B* along the wire and reading the deflection when *B* is at "10," at "20," at "30," etc.

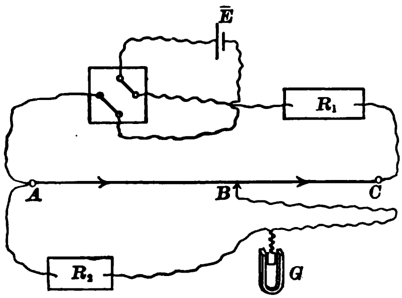

FIG. 102. — Testing the variation of electrical pressure from one point to another along a uniform wire.

Make a similar set of readings in the opposite direction, beginning with *B* at "100" and moving it toward *A*. If the time permits, reverse the direction of the current in the stretched wire and make another similar set of observations. Record your results in a table as follows:

Obs.	Position of *B* reading up the Scale	Deflection of Galvanometer	Position of *B* reading down the Scale	Deflection of Galvanometer
1	10		10	
2	20		20	
3	30		30	
etc.	etc.		etc.	

(*d*) Your have now obtained the electrical pressure corresponding to various lengths of circuit, ranging, say from 10 to 100 cm. Proceed to plot these lengths as abscissas and the electrical pressures (galvanometer deflections) as ordinates. The curve which results will answer the question as to how the electrical pressure between any two points varies with the length of wire between the same two points *when the current remains constant.*

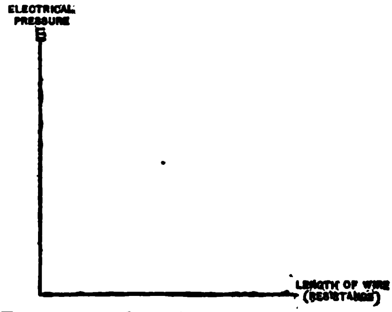

Fig. 103. — Graphical representation of Ohm's Law, applied to a uniform wire. Curve to be drawn by student.

As one passes along the stretched wire from *A* to *B*, the cross-section and the material of the wire remain practically constant. Is it, or is it not, allowable therefore, to say that the resistance of wire between any two points *A* and *B* is proportional to the length of wire between *A* and *B*? Why?

What do you consider the principal source of error in this experiment?

Exercise 82. — Further Study of Fall of Electric Pressure along a Wire conveying a Current

References. — Crew, 320–323; Rowland and Ames, 132; Hall and Bergen, 419–424; Wentworth and Hill, 290, 292; Avery, 352; Gage, 320; Carhart and Chute, 364, 349–350.

Apparatus. — Same as the preceding, with the following exception; namely, instead of the stretched brass (or german silver) wire, use a wire made by soldering together four wires, as shown in Fig. 104, where

AB is 10 cm. of iron wire, approximately 0.25 mm. in diameter.
BC is 20 cm. of iron wire, of the same diameter as *AB*.

CD is 20 cm. of copper wire, of the same diameter as *AB*.
DE is 20 cm. of iron wire, approximately 1.00 mm. in diameter.

Short terminals of copper wire may be soldered on at the points *A, B, C, D, E,* if desired.

Problem. — To study the manner in which the electrical pressure varies from one point to another along a conductor conveying a constant current. In particular, to find how the difference of electrical pressure varies with the *cross-section* and with the *material* of which the wire is made. A partial verification of Ohm's Law.

Experiment. — (*a*) Join a single dry cell to the wire *ABCDE*, as shown in Fig. 104. Hold (or fasten) one terminal of your galvanometer at the end *A*, and the other terminal at the point *B*, which is one-third of the distance from *A* to *C*. Record the deflection of the galvanometer.

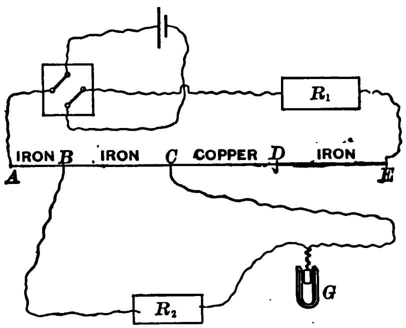

Fig. 104. — Testing the variation of electrical pressure along a wire which varies in cross-section and in material.

(*b*) Move the terminals of the galvanometer along, so that one of them is in contact with the point *B*, the other with the point *C*. How does the deflection compare with that between the points *A* and *B*? How does the length *BC* compare with length *AB*?

(*c*) Move the terminals along, so that they are in contact with *C* and *D*. Record the deflection. What difference is there between the wires *BC* and *CD* that causes the difference in electrical pressure? Note that *CD* has the same length, the same cross-section, and the same current as *BC*; and yet the difference of electrical pressure between its ends is small compared with that between the ends of *BC*.

(*d*) Move the terminals along to *D* and *E*, and measure the

electrical pressure between these two points. How does the deflection compare with that between B and C? How does the cross-section compare with that of BC? Make a summary of the facts that you have observed in this exercise, and in Exercises 79 and 81, stating just what things the difference of pressure along the wire depends upon.

When the current is constant	
Difference of pressure depends upon	Heat developed depends upon

ELECTRICAL RESISTANCE

As has been already pointed out (p. 174), the electrical resistance of a wire, or of any conductor, is a constant which depends upon the length, cross-section, and material of the conductor.

Electrical resistance may be defined in either of the two following ways; namely, (1) as the ratio of electrical pressure to current, or (2) as a quantity which determines how much heat a given current will produce in a given time. These two definitions are exactly equivalent. (See Crew's *Elements of Physics*, Arts. 312, 322.)

UNIT OF RESISTANCE

To measure an electrical resistance — say the resistance of copper wire — in terms of other and known quantities is not a

simple matter. Indeed, it is a very difficult problem. But to compare one resistance with another known resistance is a comparatively easy matter. The value of a known resistance is generally and naturally expressed in terms of the unit of resistance, that is, in terms of the "ohm." The **amount of resistance** in an ohm is the same as that in a column of mercury of uniform cross-section at 0° C., when its length is 106.3 cm. and its mass is 14.4521 grammes. Just *why* a resistance of this particular size is chosen for a unit is a highly interesting question, but one which may well be left for advanced study.

The following exercise illustrates an exquisite method for comparing the resistance of one conductor with that of another:

Exercise 83. — Measurement of Resistance by Wheatstone's Bridge

References. — ROWLAND AND AMES, 133; HALL AND BERGEN, 425; CARHART AND CHUTE, 365; AVERY, 416; WENTWORTH AND HILL, 293; GAGE, 328.

Apparatus. — A Wheatstone's bridge of "slide wire" form; sensitive galvanometer; single dry cell; commutator; key; two wires whose resistances are to be compared. One of these two wires may be a known standard resistance.

Problem. — To compare the electrical resistance of one wire with that of another. An application of Ohm's Law. The very elegant method here employed was devised by the English inventor, Charles Wheatstone (1802–1875).

Experiment. — It is here taken for granted that you have learned from your preceding work that *the resistance between any two points on a conductor which carries a constant current, varies directly as the difference of electrical pressure between those two points.* This is the fundamental principle of the Wheatstone bridge; and the instrument is very simple to any one who understands this principle, while it is apt to appear very complex to any one who does not understand it.

any two points on a conductor, we

$$\frac{\text{ressure between the two points}}{\text{between the same two points}},$$

bra,

$$C = \frac{E}{R}.$$

ent is constant, E varies as R. This
in Wheatstone's bridge, which con-
res joined in parallel, and thus form-
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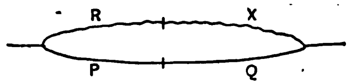

FIG. 105. — The two parallel branches of a Wheatstone bridge.

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you
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d in
which is furnished you there will probably be found two binding-posts to receive the resistance R, and two to receive the resistance X. The wire PQ is usually a straight wire a metre long, and mounted on the wooden base of the instrument.

(*b*) Having joined up the conductors R and X, as indicated, proceed to connect a single voltaic cell to the points A and D, as shown in Fig. 106. The current enters the bridge at A, there divides into two parts, one passing along the branch RX, and one along the wire PQ.

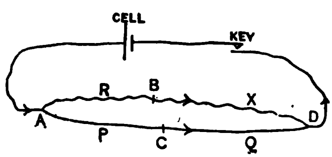

FIG. 106. — Showing how the battery is connected in a Wheatstone bridge, and how the current divides.

(*c*) Let us now consider the electrical pressure at the point B, where the two resistances, R and X, meet. The pressure at B is evidently less than at A, and higher than at D, for the current is constant throughout the entire length of R and X. And since the electrical

pressure at B is intermediate between those at A and D, there must be some point on the wire PQ which has the same pressure as that at B. Let us suppose that we have already found this point on PQ; for, as we shall see in a moment, this is very easily done. Let C (Fig. 106) be the point that has the same pressure as B. This point C will divide the conductor PQ into two parts which we may call P and Q; and since the current in R is the same as the current in X, we may write

$$\frac{\text{Fall of pressure in } R}{\text{Resistance of } R} = \frac{\text{Fall of pressure in } X}{\text{Resistance of } X};$$

and since the current in P is the same as the current in Q, we may write

$$\frac{\text{Fall of pressure in } P}{\text{Resistance of } P} = \frac{\text{Fall of pressure in } Q}{\text{Resistance of } Q}.$$

Since the point C has been so chosen that the fall of pressure in R is the same as the fall of pressure in P, and the fall in X the same as the fall in Q, then dividing one of the above equations by the other, we have

$$\frac{\text{Resistance of } R}{\text{Resistance of } P} = \frac{\text{Resistance of } X}{\text{Resistance of } Q};$$

or, in the shorthand of algebra,

$$\frac{R}{P} = \frac{X}{Q}. \quad \textbf{Equation of Wheatstone's bridge.}$$

This equation tells us that the unknown resistance X is $\frac{Q}{P}$ times that of R. Our problem is solved, then, as soon as we learn how to find the point C which has the same electrical pressure as B. This is done as follows:

(*d*) Join one terminal of a galvanometer to the point B. Take the other terminal of the galvanometer and touch it to the wire PQ; you will obtain a small current through the galvanometer. Now move the terminal along the wire PQ until you reach a point where there is *no* current in the galvanome-

ter. This is the point C, which has the same electrical pressure as the point B; for if there were any difference of pressure between B and C, there *would* be a current in the galvanometer. But as you have seen above, the point C thus determined divides the slide wire PQ into two parts, P and Q, such that

$$X = \frac{Q}{P} R.$$

So that, if we know the ratio of the resistance Q to the resistance P (which can be obtained by measuring the lengths of P and Q), we can find the value of the resistance X in terms of the resistance R; and this is the object of the experiment.

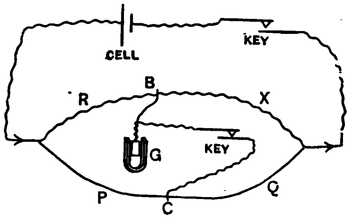

FIG. 107.—Diagram of Wheatstone's bridge in its completed form.

Instead of using one key in the battery branch and another in the galvanometer branch, it is customary to employ two keys mounted on the same block, so that we can close both keys at one stroke of the finger. Such an arrangement is called a **double contact key**. This key should always be connected in such a way that the battery branch shall be closed before the galvanometer branch. The reason for this must be left for the more advanced student.

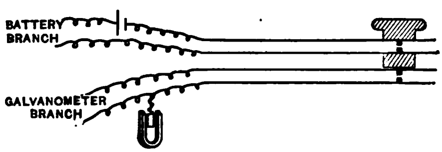

FIG. 108.—Key for making two contacts in succession.

(*e*) Having measured the value of X in the manner indicated above, interchange the resistances R and X, and repeat the measurement.

(*f*) If time permits, reverse the direction of your battery current, and repeat the measurement.

CHAPTER X

LIGHT

Mastery of the various departments of Physics calls for accurate laboratory work and clear deliberate thinking. In the study of optics this is especially true. And yet the careful student will be surprised at the simplicity of the apparatus necessary to pursue this science.

Of the following exercises, the first four are intended to give the student some insight into the nature of light, and to furnish him with irrefutable evidence for thinking that light consists in a wave-motion, the phenomena here studied being precisely those which are observed in all kinds of wave-motion. The remaining seven exercises are devoted entirely to the application of the fundamental principles established in the first four experiments.

Exercise 84. — Fundamental Phenomena in Optics

References. — Crew, 329; Carhart and Chute, 559; Avery, 315; Wentworth and Hill, 419.

Apparatus. — A lamp (preferably an Argand lamp) with a tin chimney; a postal card; a pocket-knife. On one side of the tin lamp-chimney should be drilled a circular hole from 2 to 4 mm. in diameter, on a level with the brightest part of the flame; on the opposite side of the chimney should be cut a narrow slit, 1 or 2 mm. wide and 15 or 20 mm. long.

Problem. — To study the behavior of light passing through small openings; and to show that under these circumstances

it behaves very much as we know water-waves and sound-waves to do.

Experiment. — (*a*) Take a lamp which is provided with a tin chimney, having in it a small circular hole from 2 to 4 mm. in diameter. If this hole is close to the flame, you may consider it as a luminous point — or point-source — sending out rays of light in all directions from which it can be seen.

(*b*) Take a postal card and cut a slit in the edge of it with a sharp pocket-knife or pair of shears. Place the lamp at a distance of 5 or 10 feet from you. Hold the postal card close against your eye, as indicated in Fig. 109, and look through the slit at the little hole in the lamp-chimney. The hole does not appear circular as it did to the naked eye. Make a sketch in your note-book of the image of the circular hole as seen through the slit in the card.

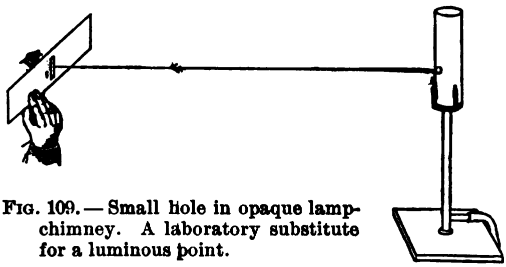

FIG. 109. — Small hole in opaque lamp-chimney. A laboratory substitute for a luminous point.

(*c*) Again hold the card close in front of your eye and rotate the slit around the beam of light as an axis while you are viewing the source of light through it. Does the image of the source rotate with the slit?

(*d*) Now look through the slit again, and, *while you are looking*, change the width of the slit by alternately pulling the sides slightly apart and pushing them together again. As the slit becomes wider, how does the image change? Does it increase or diminish in width? Record the fact in your note-book.

(*e*) Now turn your lamp around (or, in case the lamp is fixed, pass to the other side of it), and examine in the same way a long narrow slit in the lamp-chimney. What do you

observe when you hold the slit of the postal card parallel to the slit of the lamp-chimney? What is the effect of holding the slit in the card at right angles to the slit in the lamp-chimney?

(*f*) Make a sketch in your note-book of the manner in which you have found the direction of the rays changed on passing through a narrow slit. Let *S* (Fig. 110) indicate the point-source of light, and *C* a section of the slit in the card. How are the rays from *S* affected on passing through the opening in *C*?

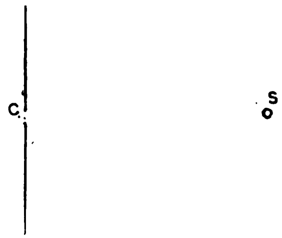

FIG. 110.—The manner in which rays of light bend around a corner. Diagram to be completed by student.

If a train of water-waves, coming from the right, as shown in Fig. 111, were to strike an opening in a breakwater, what effect would you expect these waves to produce upon the quiet water to the left, judging from your previous observations of water waves? Would the disturbance pass straight on through the small opening, or would it spread out into a fan-shaped disturbance?

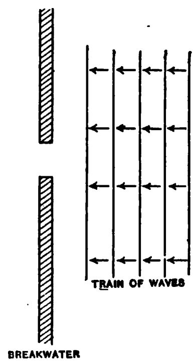

FIG. 111.

This phenomenon of spreading out is called **diffraction**, which is merely the Latin word for *bending apart.*

(*g*) If time permits, make three pinholes in a visiting card, or better, in a piece of tinsel, or stencil-maker's brass. Let the first hole be as small as you can make it, another the size of an ordinary pin, and the third one intermediate in size between the two preceding. Now examine the point-source of light through these three holes in succession. Through which hole does the source look smallest? Through which does it look largest?

Exercise 85. — Reflection at a Plane Surface

References. — Crew, 331, 332; Rowland and Ames, 141–142; Hall and Bergen, 106–109; Avery, 269–276; Carhart and Chute, 488–495; Wentworth and Hill, 369–372; Gage, 227–229.

Apparatus. — Mirror, made of a strip of plate glass about 6 inches long and 1 inch wide, coated on one side with a film of polished silver; or, if preferred, the natural surface of the glass, without any silver, may be used as the reflecting surface, — in either case it is best to grind the back surface of the glass with emery, or to paste paper over it; rectangular block of wood, to which the mirror may be fastened by cement or rubber bands, so that it will stand upright, its long edge resting on the table, — the width of the mirror should be slightly greater than the height of the block; drawing-board, or other smooth board of soft wood, — one a foot square will be large enough for this and the following exercises; draughtsman's triangle of wood or hard rubber; paper, pencil, pins; protractor; millimetre scale.

Problem. — To show that when light is reflected at a plane surface, the angle of incidence is equal to the angle of reflection; also that the object and its image are at equal distances from the reflecting surface; and that the line joining them is perpendicular to the surface.

Experiment. — (*a*) Lay the paper on the board and draw across it a straight line LL'. Place the mirror with the reflecting surface toward you, so that its lower edge lies along LL', as in Fig. 112. In front of the mirror set up vertically two pins, as at A and B. The *images* of A and B, as seen in the mirror, will be behind the reflecting surface at A' and B' respectively. Place your eye in line with A' and B'. To fix the direction of this line, set up two more pins in front of the mirror, as at C and D.

Now remove the mirror and pins. Draw the lines AB, CD, by joining the centers of the pinholes. These lines should meet

at some point M on LL'. AB marks the direction of an incident ray, and CD that of the same ray after reflection. By aid of a right-angled triangle draw MN perpendicular to the reflecting surface, *i.e.* to LL'. The angle AMN between the incident ray and the normal is called the **angle of incidence**, and the angle DMN between the reflected ray and the normal is called the **angle of reflection**. Measure these two angles with the protractor, and record their values in a table. Make about five sets of measurements, using a new angle of incidence each time. How do the angles of reflection compare with the corresponding angles of incidence?

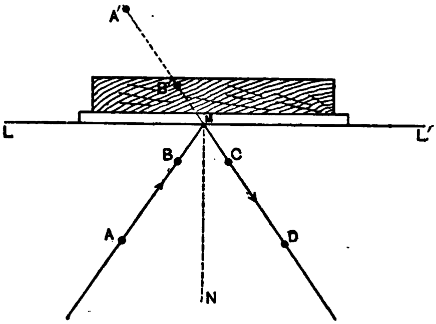

FIG. 112.—Reflection of light at a plane surface.

(*b*) On another sheet of paper draw a straight line LL', and make the lower edge of the reflecting surface coincide with this line as before. In front of the mirror, and several centimetres from it, set up a pin as at A in Fig. 113. Viewing the image of A in the mirror, set up a second pin as at B, so as to *coincide exactly* with the image of the first pin.

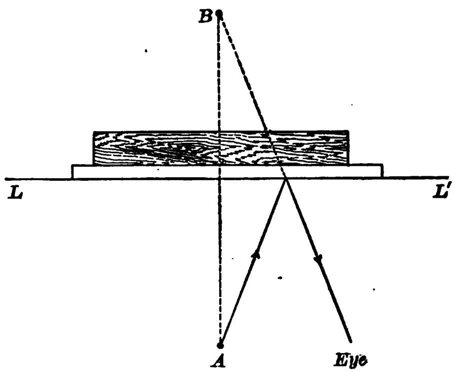

FIG. 113.—A method of locating the image in a plane mirror.

When this is the case the top of the pin B, seen *above* the mirror, will appear to be a prolongation of the image of A seen *in* the mirror, and this will be true *from whatever direction they are viewed.*

It is important to note that if, on moving your head to one side, the pin at B and the image of A appear to separate, then *the one which moves in the same direction as your head is the one which is farthest from the mirror.* The position of B must then be changed until it remains at all times in coincidence with the image.

Having thus marked the position of the image, measure the distance of both A and B from LL'. Repeat this, making about five sets of measurements, changing the position of A. Record these distances in a suitable table. How does the distance of the object from the reflecting surface compare with the distance of its image?

By means of a protractor measure the angle between the reflecting surface LL', and the line AB, joining the object and image. What values do you find for this angle?

Exercise 86. — Refraction

References. — Crew, 335–338; Rowland and Ames, 145–146; Hall and Bergen, 127–128; Carhart and Chute, 508–512; Avery, 284, 287; Wentworth and Hill, 381; Gage, 232–234.

Apparatus. — Block of glass with two parallel sides, and at least an inch thick, — if this is not to be had, several thicknesses of plate glass clamped together will answer the purpose very well; smooth board, as in the preceding exercise; right-angled triangle; pencil compass; millimetre scale; pins, preferably "entomological pins"; paper.

Problem. — To study the change of direction of a ray of light on passing from one transparent medium into another.

Experiment. — Draw on paper a straight line LL'. Stand the block of glass on edge, so that the face nearest you lies accu-

rately along LL'. This face will be the refracting surface. Set up a pin *vertically* at some point A, in contact with the back surface of the glass, and another at some point B, in contact with the refracting surface. With one eye look *through the glass* in such a direction as to bring A and B apparently into line with each other. In the same line set up a third pin C, several centimetres from B.

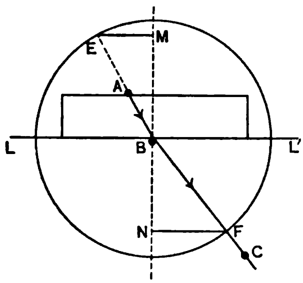

FIG. 114. — Change of direction of a ray on passing from one medium into another.

Remove the glass and pins, and with a *sharp* pencil join BA and BC. At B draw MBN perpendicular to the refracting surface. CBN is called the angle of incidence, and ABM the angle of refraction. With B as centre, draw a circle with a *radius* of 6 or 8 cm., meeting BA and BC in the points E and F. From E and F draw EM and FN perpendicular to MN.

Measure the lengths of EM and FN, and record these in a table. Record also the ratio $\frac{FN}{EM}$. Make five sets of measurements of these quantities, each time changing the angle of incidence. Choose the points A and B so that the angle CBN shall never be much more than 45°, otherwise it will be difficult to make accurate measurements.

How do your values of the ratio $\frac{FN}{EM}$ compare with each other? This ratio is known as the index of refraction for the particular kind of glass you have been using.

Exercise 87. — Further Evidence for the Wave Theory of Light

References. — CREW, 342, 343; ROWLAND AND AMES, 135, 136; CARHART AND CHUTE, 556; AVERY, 314–315; WENTWORTH AND HILL, 418; GAGE, 269.

Apparatus. — A lamp with a tin chimney such as that described in Exercise 84; a piece of photographic plate such as is used for making lantern slides; a sharp pocket-knife and a small ruler. The film of a "rapid" photographic plate is much harder to cut with a knife than that of a "slow" plate. A single lantern slide plate can be cut up into six pieces, each of which will be large enough to supply one student for the purposes of this experiment.

Problem. — To add together two rays of light and thus produce darkness. The possibility of doing this is perhaps our most direct evidence for thinking that light consists in a wave-motion.

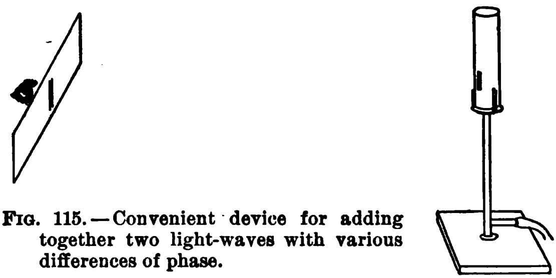

Fig. 115. — Convenient device for adding together two light-waves with various differences of phase.

Experiment. — (*a*) Take a lamp which is provided with a tin chimney having in it a narrow slit, say from 1 to 2 mm. in width.

(*b*) Take a small piece of photographic plate — a piece of lantern slide is best — and, by means of a small ruler and pocket-knife, cut two fine parallel lines in the film of the plate. These two rulings should be not more than $\frac{3}{10}$ of a millimetre apart; the closer together the better. If the ruler is held down firmly, and if your knife is sharp, there will be no difficulty in making these rulings at first trial.

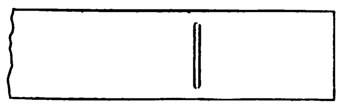

Fig. 116. — A pair of rulings $\frac{3}{10}$ mm. apart.

(*c*) Now proceed to examine the slit of the lamp-chimney through the pair of slits which you have made in the photo-

graphic plate. If your rulings are close enough together (less than $\frac{3}{10}$ mm.), you will observe a beautiful phenomenon. For each ruling will admit a pencil of rays to your eye, so that two trains of light-waves, each coming from the same source (and therefore leaving the point *S*, Fig. 117, in the same phase), will be admitted to your eye. These two pencils will spread out as they pass through the apertures *O* and *O'*, and will overlap in the region *BA'*; that is, the region *BA'* will be illuminated with light from both the apertures *O* and *O'*.

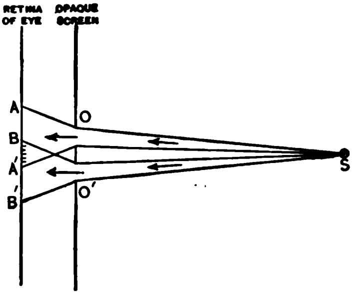

FIG. 117.—Young's experiment. Interference of two pencils which overlap owing to diffraction.

Indeed, we shall not be far wrong if we consider the apertures *O* and *O'* as two sources of light, each sending waves to the retina of the eye. At any point on the screen—the retina—where the distance to *O* (Fig. 117) differs from the distance to *O'* by a whole number of wave-lengths, there will be a bright region. But at any point where these two distances differ by $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, etc., of a wave-length, the two rays will always annul each other, and their joint effect will be to produce darkness. This state of affairs is fairly represented in Fig. 118.

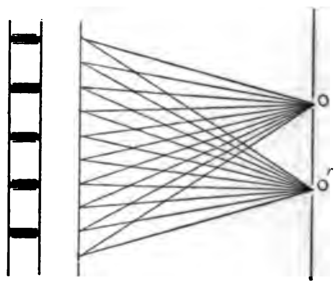

FIG. 118.—Alternate bright and dark bands produced by the interference of two pencils.

(*d*) Now rule another pair of slits on the photographic plate, making them a little *closer together* than the pair you have just used. How does this change affect the distance apart of the bright bands in the image?

(*e*) Rule a third pair of slits, making them a little *farther apart* than the first pair. What effect upon the distance apart of the bright bands in the image?

The beautiful series of colors which here make their appearance are due to the fact that the bright and dark bands are farther apart for colors of longer wave-lengths, such as orange and red, and closer together for the colors of shorter wave-lengths, such as blue and violet.

Exercise 88. — Displacement produced by a Parallel Plate

References. — Wentworth and Hill, 384; Avery, 287; Hall and Bergen, 132; Gage, 233; Carhart and Chute, 513.

Apparatus. — The same as in Exercise 86, with the exception of the pencil compass.

Problem. — To find what changes in the position and direction of a ray of light are produced by passing it through a plate of glass whose sides are parallel.

Experiment. — (*a*) Lay a plate of thick glass on edge, and trace on paper each of its parallel sides with a sharp pencil. Set up two vertical pins behind the plate, as at *A* and *B*, Fig. 119.

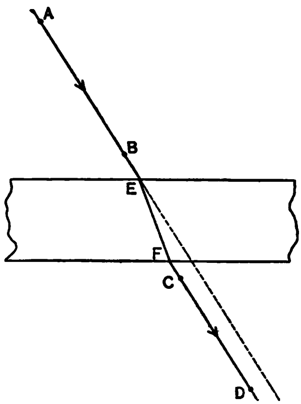

Fig. 119. — Passage of a ray of light through a piece of plate glass.

Looking through the glass, set up two more pins, *apparently* in line with *A* and *B*, as at *C* and *D*. Remove the block of glass and the pins. Join the centres of the pinholes at *A* and *B* with a sharp pencil and ruler, prolonging the line through the space previously occupied by the glass plate, as shown in Fig. 119. Also join *C* and *D*, continuing the line until it meets the front surface of the plate.

Is the *direction* of a ray changed on passing through a parallel plate? (Measure the perpendicular distance between the line AB and the line CD at two places some distance apart, and so find whether they are parallel.)

Join the points E and F, at which the ray cuts the two surfaces of the plate, and thus construct the actual path of the ray in the glass.

Make at least five trials, using various angles of incidence of the ray. In each trial measure the perpendicular distance between the incident ray and the emergent ray. Does the "displacement" of the emergent ray increase or diminish as the angle of incidence is increased?

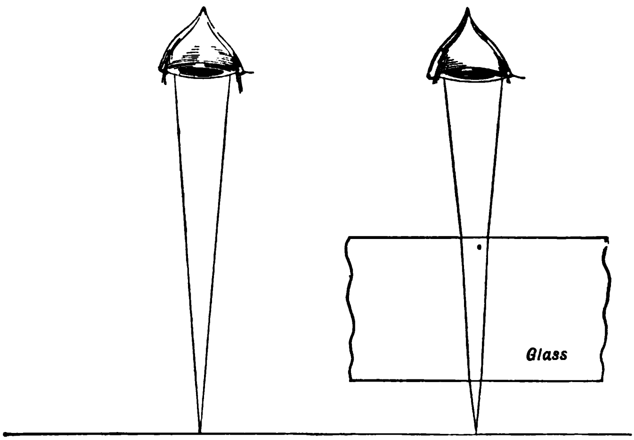

FIG. 120.—Illustrating the fact that objects appear nearer when seen through a block of glass with plane parallel sides. Diagram to be completed by the student.

(*b*) Lay the block of glass flat upon a printed page. Look down on the block from a point above it. That part of the print which is covered by the glass is apparently raised above the rest of the page. The same is true if the block of glass be taken up from the paper and held between it and your eye. Explain this "lifting power" of a refracting substance by pro-

ducing backward the rays which have passed through the block and are about to enter the eye (Fig. 120, right-hand side).

Remember that a point always seems to be situated at the place from which the rays entering the eye *appear* to diverge.

Exercise 89.—Path of a Ray through a Prism—Dispersion

References.—Crew, 346; Rowland and Ames, 147; Hall and Bergen, 133; Carhart and Chute, 514–515; Wentworth and Hill, 385; Gage, 238; Avery, 288–289.

Apparatus.—Triangular glass prism with one flat end (a 60° prism answers well). If the back surface is not rough ground, it is a good plan to paste paper over it to avoid confusing reflected rays with refracted ones. Prang's or Bradley's colored papers: red, green, blue, violet, and black — (the sample books of these papers which may be had for a very few cents from dealers in school supplies, contain abundant material for this exercise); sheet of paper; pins; pencil; ruler; smooth board.

Problem.—To study the path of a ray of light on passing through a prism; and also to show that rays of different colors are differently affected by a prism.

Experiment.—(*a*) Lay a sheet of white paper on a smooth board, and set up two pins (D and E, Fig. 121) a few centimetres apart. In line with these pins, and near one of them, stand a prism on end, and turn it into such a position that you can see the two pins through it, as in Fig. 121.

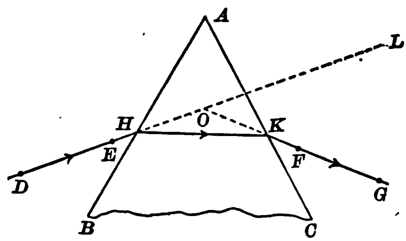

Fig. 121.—Showing the deviation produced in a ray of light by a prism.

These two pins D and E mark the direction of a ray incident on the side AB of the prism. Looking into the opposite side AC, set up two pins

at F and G, *apparently* in the same straight line with D and E.

Now trace an outline of the base of the prism on the paper; then remove the prism and pins, and draw the lines DE and FG, producing each of these to meet the prism. If H and K are the points at which these rays intersect the refracting surfaces, then HK will be the path of the ray in the prism. Do you find that the emergent ray is parallel to the incident ray, as in the preceding exercise, where the sides of the glass were parallel? If not, do you find the emergent ray bent toward the refracting edge A, or away from it? The angle GOL, through which the ray has been bent, is called the **angle of deviation.**

Make at least three trials of the above experiment, using different angles of incidence upon the prism. Do you find that the angle of deviation is constant, or does it vary with the angle of incidence?

(*b*) On a sheet of black paper draw a straight line 5 or 6 inches long. Cut some narrow strips of colored papers about 2 cm. long, and 2 mm. wide,—one each of red, yellow, green, blue, violet, and white. Paste these end to end along the pencil line on the black paper, making a continuous band 2 mm. wide.

Hold the prism in your hand close to your eye, with the refracting edge parallel to this band. With a little practice you will be able to see the band of colors through the prism. Do the various colors appear to remain in line? If not, make a list of them, arranging them in the order of their apparent nearness to the refracting edge. Would you say that rays of different color are equally deviated on passing through a prism or not? If not, which color is most deviated, and which least? Do you find that each of these papers reflects a single color, or does the prism show that some of them reflect several colors? In other words, does the red paper contain any blue, the yellow any green, etc.? How many of the above colors can you detect in the white paper? Would it be allowable to infer that this white is a mixture of all other colors?

Since different colors are unequally deviated by a prism, this instrument furnishes us a means of separating the various colors contained in any mixture, and thus enables us to determine whether any particular kind of light consists of a single color, or is a mixture of several. This is the fundamental principle of spectrum analysis.

PARALLAX

Let *M* and *N* (Fig. 122) represent two lights seen at night by an observer at a distance. If the lights are close together, it is sometimes difficult to judge which of the two is the nearer. To an observer at *A*, in line with *M* and *N*, they will appear to coincide with each other. But if the observer moves to the right, say to *B*, the lights will appear to separate, and *M* will seem to move to the right of *N*. On the other hand, if the observer moves to a point *C*, on the left of *A*, *M* will appear to move to the left of *N*. So that always, *the light which appears to move in the same direction as the observer is the more distant one.*

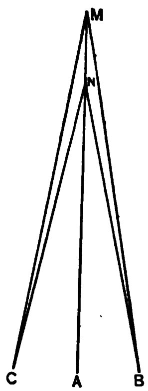

FIG. 122. — Use of the method of parallax to determine which of two points is more distant.

If, however, the observer, on moving sidewise from *A*, should find that the lights do not move apart, he would know that the lights were equally distant from him, one of them being vertically above the other.

An excellent illustration of the same thing is furnished by the apparent motion of objects seen from a moving train. If a passenger fixes his attention upon a definite object, such as a tree, at a distance, all objects beyond the tree appear to move forward, *i.e.* in the direction of the train's motion, while objects nearer than the tree appear to move backward.

This apparent change in the relative position of two points

when the position of the observer is changed, is called **parallax**; and the above-described method of determining which of two points is the nearer, or whether they are equally distant, by changing the point of view, has been called the "method of parallax."

Exercise 90. — The Concave Mirror

References. — Crew, 351, and last paragraph of 353; Rowland and Ames, 144; Hall and Bergen, 113–121; Carhart and Chute, 499–502; Avery, 279–281; Wentworth and Hill, 374–378; Gage, 230–231.

Apparatus. — Concave mirror which may be made by silvering one side of a large watch-glass; at the centre of the mirror scrape off a narrow strip of silver about 10 mm. long and 2 mm. wide, in order to allow the observer to see through the mirror; mount the mirror upright on a block of wood, or secure it by one edge in a clamp, the slit in the film being placed horizontal; two pieces of a steel knitting-needle, each mounted upright in a small wooden block, with their upper ends at the same height as the centre of the mirror surface; wooden millimetre scale, having a corner cut off at the zero end (as indicated in Fig. 123), so that when placed against the mirror surface it will touch it at one point only.

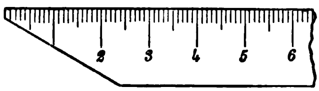

Fig. 123. — Wooden scale, adapted to measurement of distances from surface of mirror.

Problem. — To study the image formed, when light is reflected at a concave spherical surface.

Experiment. — (a) For the object whose image is to be studied, we shall use the tip of one of the upright needles. Place the object in front of the mirror, and a foot or more from it, and find the image. If you do not see it at first, on looking past the object into the mirror, rotate the mirror a trifle; the image will then change its position slightly, and may thus be more easily recognized. The image will probably be inverted and smaller than the object. If it is not, move the

object farther away from the mirror. Having obtained an image which is inverted and smaller than the object, proceed to move the object slowly toward the mirror. Does the image move toward the mirror or away from it?

You will presently find a point at which the image is vertically above the object, and of the same size as the object. Make the end of the image coincide with the end of the object. The point so determined is called the **centre of curvature** of the mirror, and is the centre of the sphere of which the mirror surface is a part. For every ray which leaves the point of the needle returns along the same path by which it travelled toward the mirror. Thus each ray of light which falls on the mirror from the centre of curvature C (Fig. 124) travels along a radius of the sphere, being reflected at right angles from the mirror surface.

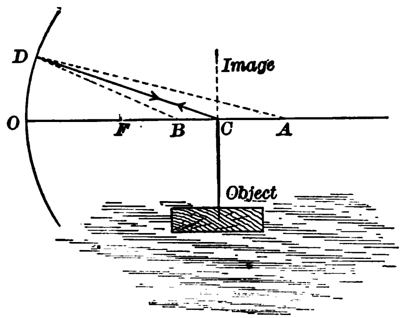

FIG. 124.—Image and object coinciding at centre of curvature of a concave mirror.

Rays from an object at some point A, beyond the centre of curvature, will, however, form an image at some point B, between the centre of curvature and the mirror; while it is equally true that rays from a point B will be reflected to a point A.

Continue to move the object toward the mirror. The image will move farther and farther from the mirror, until it has receded to an indefinitely great distance. As the object is moved still closer to the mirror, you will presently observe that the image appears *behind* the mirror, and is erect, while before it was inverted and in front of the mirror. The line CO, joining the centre of curvature and the centre of the mirror, is called the **axis** of the mirror. *The position of the object on the axis*

at which the image changes from front to back of the mirror, is called the **focus** (F, Fig. 124).

(*b*) Placing the object somewhere in front of the mirror, mark the position of the image with the second wire. Make this image and the second wire coincide accurately, by the method of parallax, explained on p. 199. Now measure the distances of the object and image from the mirror. Make six sets of measurements as follows: two when the object is beyond the centre of curvature; two when the object is between the centre of curvature and the focus; and two when the object is between the focus and the mirror. In the last of these positions it will be necessary to place the second needle behind the mirror, and to bring it into coincidence with the image by looking through the narrow slit in the silvered film.

Enter your results in a table like the one given below, in which u represents the distance from the mirror to the object, and v the distance from the mirror to the image. v must, of course, be considered *negative when the image is behind the mirror.*

(*c*) From the values of u and v calculate, for each observation, the value of the expression $\frac{1}{u}+\frac{1}{v}$. What relation do you notice between the different values of this quantity? If we write $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$, then f is a constant, whose numerical value is the value of the **focal length of the mirror**. The focal length of a mirror is numerically equal to the distance from the focus to the mirror, measured along the axis.

Obs.	u	v	$\frac{1}{u}+\frac{1}{v}$	f	R	
	cm.	cm.		cm.	cm.	
1						
2						
3						
etc.						

(*d*) Bring the object to the centre of curvature by making it coincide with its image, using the method of parallax. Measure the radius of curvature six times, and record its values in the column headed "*R*."

What relation between f and R do you notice. If you do not see this from inspection, compute the values of $\frac{R}{2}$, and place them in the last column of the table.

Exercise 91. — The Convex Mirror

References. — ROWLAND AND AMES, 144; AVERY, 283; HALL AND BERGEN, 113–121; WENTWORTH AND HILL, 374–378; CARHART AND CHUTE, 502–503.

Apparatus. — The same as in the last exercise, using the other side of the watch-glass.

Problem. — To study the image formed by a convex mirror; an image which is always virtual.

Experiment. — (*a*) Place one of the mounted needles in front of the mirror for an object. Look for the image. Do you find it in front of or behind the mirror? Is it larger or smaller than the object? Place the object at different distances from the mirror and find whether your answers to the above questions are true in *all* cases.

(*b*) Having set up the object in front of the mirror, bring the second needle to coincide accurately with the image of the first needle. Do this by the method of parallax (p. 199), looking through the opening in the silver coating on the mirror. Measure the distances of the object and the image from the reflecting surface, calling these distances u and v, respectively. As in Exercise 90, v is negative when it is measured backward from the mirror surface.

Record these values in a table, making at least five sets of measurements. Also compute the focal length of the mirror, f, from the formula $\frac{1}{f}=\frac{1}{u}+\frac{1}{v}$, and record your values of f in the last column.

Is the focal length of a convex mirror positive or negative? What does it mean when you obtain a negative value for f?

Exercise 92. — Study of a Converging Lens

References. — Crew, 349–353; Rowland and Ames, 148; Avery, 290, 291, 293; Carhart and Chute, 524, 525, 528; Hall and Bergen, 136–140; Wentworth and Hill, 386–390; Gage, 239–242.

Apparatus. — Simple "optical bench," consisting of a metre stick mounted flat on a horizontal board, and three wooden holders for object, lens, and screen, the holders being arranged to slide along the metre stick; small converging lens, of 10 to 15 cm. focal length; an ordinary spectacle lens costing only a few cents answers this purpose excellently; the lens is mounted upon one of the holders, and a screen of white cardboard (or of ground glass), upon another; on the third holder mount a piece of cardboard, with a ½-inch hole cut in it at the same height as the centre of the lens; cover the hole with wire gauze to form the object, and place a lamp or gas flame behind the gauze to illuminate it; or, if preferred, daylight may be used to illuminate the object, by directing the object end of the apparatus toward the sky.

Problem. — To study the image formed by a converging lens; and at the same time to determine the focal length of the lens.

Experiment. — (*a*) For the object, whose image is to be studied, use a piece of wire gauze, placed over a hole in a piece of cardboard, and illuminated by some source of light placed behind it. Slide the object near one end of the metre stick on the base of the apparatus furnished you, and a cardboard screen near the other end, each mounted on a wooden holder. (See Fig. 125.) Place the lens at some point between the object and the screen. Move the lens back and forth on the base, and see if you can place it in such a position that a sharply defined image of the object appears on the screen. Is this image larger or smaller

than the object? Is it erect or inverted? You can determine this by partly covering the object with a card, and noting the change in the image.

(*b*) *Without disturbing the object or the screen,* find a second position of the lens in which a sharp image is formed on the screen. Is this image larger or smaller than the object? Is it erect or inverted? Is it true that the lens is always nearer the small figure, whether that figure be the object or the image?

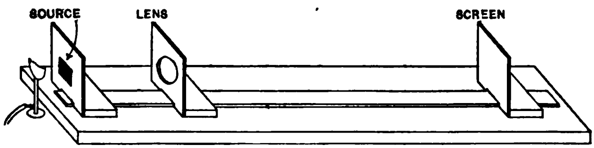

Fig. 125.—Optical bench for studying the properties of mirrors and lenses.

(*c*) Now move the screen closer to the object, and again find two positions of the lens in which an image is formed on the screen. Is it always possible to place the lens in such a position as to produce a distinct image on the screen, no matter how close together the object and the screen are placed? What is the least distance between screen and object that will permit the lens to produce a distinct image on the screen?

(*d*) Having obtained a distinct image on the screen, read from the metre stick as accurately as you can the positions of the *object, lens,* and *image.* By subtraction find the distance between the object and the lens; call this u. Also find the distance between the image and the lens; call this v. Both u and v are distances measured *from the lens,* and each must be considered *negative when measured toward the left and positive when measured toward the right.*

Calculate the value of the quantity $\frac{1}{v} - \frac{1}{u}$, giving both u and v their proper signs, and record this in the fourth column of the table. Make at least five sets of measurements of u and v, changing the distance between the object and screen. Examine

the values of $\frac{1}{v}-\frac{1}{u}$, and state whether you find them nearly alike. If we write

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{f},$$

then f is a constant for any given lens, and is approximately equal to the focal length of the lens. From each of your observations, calculate the focal length, and finally take the mean of your values.

(*e*) Now, removing the object (wire screen), take the optical bench and direct it toward a *distant* window. Use the lens to project an image of the window upon the screen. The distance of the lens from the screen will be approximately the value of the focal length of the lens. Measure this quantity five times, and record the values in the last column of your table.

Obs.	u	v	$\frac{1}{v}-\frac{1}{u}$	f (Computed)	f (Observed)
	cm.	cm.		cm.	cm.
1					
2					
3					
4					
5					

MEAN =

How many times greater than this focal length is the least distance between object and screen, measured above in (*c*)?

Exercise 93. — The Astronomical Telescope

References. — CREW, 359; ROWLAND AND AMES, 150; HALL AND BERGEN, 165; CARHART AND CHUTE, 570; AVERY, 322; WENTWORTH AND HILL, 414; GAGE, 272.

Apparatus. — Two converging lenses, one having a focal length of about 10 inches, and the other about 2 or 3 inches, — for the

first, a spectacle lens may well be used, and for the second, the lens of a pocket magnifying glass; pasteboard mailing tube an inch in diameter, and of a length about equal to the focal length of the weaker lens; strip of cardboard about 12 by 2 inches, across which heavy black lines have been ruled an inch apart (see Fig. 127); two retort stands, with clamps; millimetre scale; soft wax or gummed paper.

Problem. — A study of the combination of eye lens and object lens employed in the ordinary astronomical telescope.

Experiment. — (*a*) Find the approximate focal length of each of your lenses in the following way: Hold a millimetre scale horizontally with one end against a wall (or against a piece of white cardboard) and the other end pointed toward a distant window. Hold the lens in your hand, and, starting at the wall, move the lens along the millimetre scale until a distinct image of the distant window is formed on the wall. The distance between the lens and the wall will then be very nearly the focal length of the lens. Calling the longer focal length F_1, and the shorter F_2, record their values in a table such as that given at the end of this exercise. Determine each focal length several times.

Next calculate the *sum* of the focal lengths of your lenses, $F_1 + F_2$, and also the *ratio* of the focal lengths, $\frac{F_1}{F_2}$, and record their values in the proper columns of this same table.

(*b*) By means of soft wax, or strips of gummed paper, fasten the lens of greatest focal length flat against one end of the pasteboard tube. Secure the tube in the clamp of a retort-stand, and direct it toward some distant object seen through an open window, the end carrying the lens being nearest the window.

Now insert the second lens in the clamp of another retort-stand, and place it opposite the rear end of the tube (*E*, Fig. 126). By placing your eye close to this lens and moving the stand, you will find that when the two lenses are at a certain distance apart, distant objects are plainly visible through

them. An arrangement of this kind is a **telescope**. The lens turned toward the object is called the object glass, or **objective**; the one next the eye is the **eyepiece**, or eye lens. Rays coming from a distant point are nearly parallel, as represented in Fig. 126. These rays, after passing through the objective, meet at its focus *F*, the distance *FO* being the focal length of the objective. If the eyepiece be so placed that *its* focus is also at the point *F*, then the rays leaving *F* will, after passing through the eyepiece, be again made parallel, and in this condition are received by the eye.

FIG. 126. — An object lens and an eye lens combined to form an astronomical telescope.

Do objects viewed through the telescope appear larger or smaller than when seen with the unaided eye? Do they appear erect or inverted?

(*c*) Carefully adjust the position of the eyepiece until the image appears as distinct as you can make it. This is called "focussing" the telescope. Now measure the distance between the object-glass and the eyepiece, and record it in your table in column "Distance between lenses." Make several determinations of this distance, each time moving the eyepiece away and focussing again. How does the distance between the lenses compare with the sum of the focal lengths of the lenses?

(*d*) Take a strip of cardboard with equally-spaced heavy lines ruled across it, and fasten it on a distant wall, at the same height as your telescope. View the card through the telescope, and focus upon the lines. You are now to make a rough measurement of the magnifying power of your telescope, *i.e.* to determine how many times larger the image is than the object. To do this, view the card with *both* eyes at the same time, looking at the image through the telescope with one eye, while you view the object with the other eye, unaided by the telescope. If necessary, turn the telescope slightly, so as to make the image and object overlap, as in Fig. 127. Now, by

the parallax method, adjust the focus until the image and object appear at the same distance. They will then both be "in focus" at the same time.

The overlapping object and image should now appear much as in Fig. 127. Make some one line of the image coincide with some line of the object as shown. Count the number of spaces on the object included between any two lines of the image. This is easily done, provided you allow your eyes to remain in their natural state of repose and avoid straining them. The ratio of the size of the image to the size of the object is called the **magnifying power** of the telescope. Make several determinations of the magnifying power, and record them in your table. How does the magnifying power thus obtained compare with the ratio of the focal lengths previously obtained? Of what use is the telescope tube, aside from the fact that it supports one or both of the lenses?

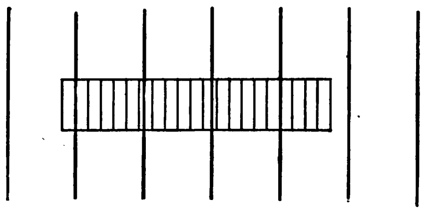

FIG. 127. — Illustrating the magnifying power of a telescope, image and object overlapping.

Obs.	F_1	F_2	$F_1 + F_2$	Distance between lenses	$\frac{F_1}{F_2}$	Magnifying power
1						
2						
3						
etc.						

STUDY OF SPECTRA

Few students realize, until they have tried the experiment, what simple means may be employed to show the fundamental phenomena of spectrum analysis. On the score of expense, no

laboratory need be without the apparatus needed for the following exercise, which, all told, does not cost more than from one to five dollars.

The set of experiments here described forms a continuous series, which may be performed in a period of two hours, but it is earnestly recommended that at least two laboratory periods be devoted to this experiment.

The lithium chloride here called for costs thirty-five cents an ounce, and the thallium sulphate one dollar for an eighth of an ounce. But these quantities are sufficient to supply a large class for several years. The superiority of these three elements for this work lies in the fact that they give single, monochromatic flames of great luminosity in widely separated parts of the spectrum.

Exercise 94. — Fundamental Phenomena in Spectrum Analysis

References. — CREW, 360; ROWLAND AND AMES, 153, 154; HALL AND BERGEN, 351–353; WENTWORTH AND HILL, 397–402; AVERY, 304–308; GAGE, 252–258; CARHART AND CHUTE, 547–555.

Apparatus. — A single 60° glass prism, costing somewhere between twenty-five cents and three dollars, according to the grade of it; a Bunsen flame; an opaque screen made of sheet iron, 12 × 12 inches, provided with a slot $\frac{1}{8}$ inch wide, as shown in Fig. 128; a few strips of ordinary thick, white blotting paper $\frac{1}{2}$ inch by 4 inches; small bit of table-salt, of sodium bicarbonate, and of lithium chloride, the size of a pea; small bit of thallium sulphate, size of a bird shot; small piece of glass tubing, say 6 inches long; any small piece of red glass; a small piece of blue glass; one or two square feet of black cloth with a dull surface.

Two students can work together with advantage upon this experiment.

Problem. — To examine several different sources of light through a prism; to discover what colors are present in the

light which these sources emit; and to learn how the spectroscope may be used to yield us information concerning various bodies that emit light and various bodies that absorb light.

Experiment. — (*a*) Take a blotter and cut from it a small narrow strip; light the end of this strip and immediately blow out the flame. The smouldering end of the strip is red-hot carbon — an incandescent solid. Proceed to examine it by holding a single glass prism close in front of your eye, as shown in Fig. 128. Let an assistant hold the blotter some three or four feet away, and keep the tip of it bright by blowing gently over it, while you look at it through the prism. (The hot filament of an ordinary incandescent lamp will serve equally well to give the colors emitted by solid carbon.) What colors do you observe through the prism?

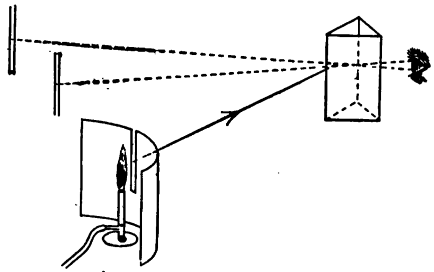

FIG. 128.—The prism as a means of separating the different colors emitted by a source of light.

This band of color into which any light is spread out, on passing through a prism, is known as the **spectrum** of the body which produces the light.

(*b*) Next examine the spectrum of an ordinary gas (or candle) flame. This is most easily done by using a Bunsen burner with the air shut off. Hold the refracting edge of the prism parallel to the flame. How does the spectrum of this flame compare with that of the solid carbon examined in (*a*)? Are there any colors missing from the spectrum of the gas flame?

(*c*) Now turn the air on the Bunsen burner and proceed to examine the "Bunsen flame" through the prism. What are the strongest colors present? What principal colors are missing?

(*d*) Let your assistant moisten a strip of thick blotting paper with a solution of ordinary table-salt (chloride of sodium). Examine the Bunsen flame while your assistant holds the *tip* of this moistened strip in the *bottom* of the flame. What color predominates over all the others? Be careful to moisten the strip so that it will not take fire.

In like manner moisten a small strip of blotter with a solution of bicarbonate of sodium. What color predominates strongly when this strip is touched to the flame? It has been found that *any* chemical compound containing sodium will give this same color.

While you are examining the Bunsen flame through the prism, allow your assistant to lift the burner half an inch above the table and set it down quickly so as to jar some dust into the flame. What color flashes out for an instant?

(*e*) Let your assistant moisten a strip of blotter with a weak solution of chloride of lithium, and present the tip of the blotter to the bottom of the flame. What color predominates? Write the name "lithium" on the strip of blotter, so that you will not get it mixed up with similar strips.

(*f*) Repeat experiment (*e*), using sulphate of thallium. A portion of this substance the size of a pinhead dissolved in a thimbleful of water will be amply sufficient for this experiment. What color, besides the omnipresent yellow, predominates? Write the name "thallium" on this strip of blotting paper.

(*g*) You have now examined the incandescent vapor of three different elements, — sodium, lithium, and thallium. Next let your assistant place in the flame any one or two (or even all) of these, without your knowing which, and see if you can tell which substance he is using. This method of detecting the presence of a substance is known as **spectrum analysis.**

The ease of distinguishing these substances will be very much increased if you take a thin piece of sheet iron and bend it into the form indicated in Fig. 128, and place the Bunsen burner behind this screen and then view the flame through the slit cut in the sheet iron.

(*h*) Having placed before the luminous or white gas flame a metal screen with a slit in it, let your assistant hold a piece of red glass just in front of the slit. What are the principal colors thus cut out of the ordinary spectrum? This ordinary spectrum in which *all* the colors are present is generally called a **continuous spectrum**.

Try the same experiment with blue glass, and record the colors which are cut out. Try the same experiment with both red and blue glasses — overlapping in front of the slit. What colors pass through both glasses? The colors which remain after some of them have been cut out in this way form what is called an **absorption spectrum**.

(*i*) If the sun is shining, place a narrow strip of white blotting paper (or white cardboard) — $\frac{1}{8}$ inch wide — on a piece of black cloth in the direct sunlight. Stand at least four feet away, and examine this white strip by looking through the prism and *holding the edge of the prism parallel to the strip.*

You find the spectrum crossed by several dark lines. How many of these lines can you observe and in what colors do they lie? Evidently the spectrum of sunlight is an absorption spectrum. It has been suggested by Kirchhoff and others that the colors which are missing from sunlight are absorbed in hot gases which surround the central portion of the sun.

These dark lines in the solar spectrum were first discovered by a German optician, Fraunhofer, and after him are known as **Fraunhofer lines**. When sufficiently powerful instruments are used many thousands of these lines can be seen in the solar spectrum; but a more minute study of these must be left for the advanced student.

APPENDIX A

(Being a note to Exercise 32)

Extract from a paper by Robert Boyle on *A New Essay Instrument, together with the uses thereof.* Published in the *Philosophical Transactions,* 1675; also in Boyle's *Works,* Vol. IV., p. 204.

"To give you now a more explicite and particular account, than I had then time to do, of the instrument, which you saw tried at the Royal Society, I shall inform you, on what grounds I devised it, and then annex some observations about the fabrick and the uses of it.

"You may remember, that many years ago I shewed you a little glass instrument, consisting of a bubble, furnished with a long and slender stem, which was to be put into several liquors, to compare and estimate their specifick gravities, and which I made use of to some purposes, for which it is not, that I know, as yet employed. But afterwards considering this little instrument somewhat more attentively, I thought the application of it might easily be, as it were, inverted, and that, whereas it was employed but to discover the differing gravities of several liquors, by its various degrees of immersion in them, it might be employed to discover the specifick gravities of several appended solids, by its being more or less depressed by them in the same liquor. For it is clearly deducible from the grounds of the hydrostaticks, that any solid body, heavier than water, looses in the water as much of the weight it had in the air, as water of equal bulk to the immersed solid would weigh in the air; and consequently, since gold is by far the most ponderous of metals, a piece of gold, and one of equal weight of copper,

brass, or any other metal, being proposed, the gold must be less in bulk, than the copper or brass. And by this means, if both of them be weighed in the water, the gold must loose in that liquor less of its former weight than the brass or copper; because the baser metal, as well as the gold, grows lighter by the weight of a bulk of water equal to it; and the baser metal being the more voluminous, the correspondent water must weigh more than that, which is equal to the gold."

APPENDIX B

SELECTION OF A GALVANOMETER TO MEET VARIOUS REQUIREMENTS

In almost every laboratory, economy demands that a single galvanometer shall serve several different purposes. It is, therefore, desirable to select such an instrument as is, on the whole, best adapted to these various ends. Of the many uses of a galvanometer, those most commonly met with in elementary work may be classified under the following three heads:

1. The determination of two points between which there is no difference of electrical pressure, as in Wheatstone's bridge.
2. The measurement of the amount of current flowing in any circuit, as in the case where one is studying the voltaic cell or thermo-electric currents.
3. The measurement of the difference of electrical pressure between any two points of a circuit, as, for instance, when the student is verifying Ohm's Law by the fall of pressure method.

In all cases, the quantity with which the galvanometer directly deals is the current which passes through its coil. Hence the instrument must be sufficiently sensitive to detect with certainty the current in question.

In null methods, of which the first case mentioned above is a type, we conclude that the difference of pressure is practically zero whenever the deflection is zero. In order to be sure that practically no current is flowing, we must have an instrument sensitive to very minute currents.

Whenever the galvanometer is placed in series with a source of current so as to form a single circuit, the current, C, which

flows through the galvanometer, will be given by Ohm's Law as follows:

$$C = \frac{E}{R_e + R_g},$$

where E is the total electrical pressure, R_g the resistance of the galvanometer, and R_e the resistance of that part of the circuit which includes the source of electromotive force and which is external to the galvanometer coil.

We may here distinguish three cases.

I. Suppose that the resistance of the circuit, external to the galvanometer coil, is very high in comparison with the resistance of the galvanometer; *i.e.* R_e is large in comparison with R_g. Then we have practically

$$C = \frac{E}{R_e}.$$

In other words, the introduction of the galvanometer into the circuit has not appreciably affected the current strength, and, therefore, such an arrangement is well adapted to the measurement of the current in the circuit. A galvanometer used in this manner is called an **ammeter**.

II. Suppose the resistance of the galvanometer very high, so that R_e may be neglected in comparison with R_g. We then have practically

$$C = \frac{E}{R_g}.$$

In this case, R_e has little effect on the current in the circuit, and R_g being constant, C varies directly as E. Thus, the galvanometer deflection may be taken as a measure of E, the total electrical pressure in the circuit. A high-resistance galvanometer used to measure electrical pressures in this manner is called a **voltmeter**.

In the case where the problem is to measure the difference of electrical pressure between any two points on a closed circuit, we must be careful to see that when the galvanometer terminals are applied at these two points on the main circuit

(say A and B, Fig. 102), the amount of current which is shunted off does not appreciably diminish the main current. The best way to avoid this difficulty is to make the resistance in the galvanometer circuit large in comparison with the resistance of that portion of the main circuit between the terminals of the galvanometer. For this reason a resistance coil is placed in series with the galvanometer in Exercises 81 and 82.

III. Passing now to the general case where neither R_e nor R_g can be neglected, it may be shown (though the proof must be here omitted), that in general the sensibility of the galvanometer is greatest when the resistance of its coil is equal to the resistance of the external circuit. In other words, with a given source of electrical pressure, the deflection will be greatest when $R_g = R_e$.

A galvanometer to be used with an external circuit of low resistance should, therefore, have a coil of low resistance. Thus, in Exercise 76 of this volume, where thermo-electric currents are studied, and where the resistance of the whole external circuit may not exceed one ohm, a galvanometer of more than ten ohms resistance, of the type described on p. 159, will not show a readable deflection, since the galvanometer resistance is too great in comparison with the external resistance. In fact, the resistance of the galvanometer should not exceed five ohms. The same is true when we study the phenomena of electromagnetic induction, for here also the external resistance is generally small, being merely that of a small coil of copper wire.

It may be necessary, however, to use this same galvanometer to measure electrical pressure, as in Exercises 81 and 82. To thus adapt a low-resistance galvanometer of fair sensibility to the purposes of a voltmeter, it is only necessary to place a high resistance in series with the galvanometer, as suggested above and as indicated in Figs. 102 and 104.

Such a resistance, in series with the galvanometer, is also of frequent use for reducing the current strength when this is too large for the instrument, as might easily happen in Exercise 73. The same result may also be attained by the use of a **shunt**, that

is, a short wire of low resistance placed across the galvanometer terminals. A shunt of sufficiently low resistance to divert the greater part of the current from the galvanometer should be used in all cases in which a voltaic cell is connected directly to a sensitive galvanometer, as in Exercise 73.

The resistance, R, of a shunted galvanometer may be obtained from the following expression:

$$\frac{1}{R}=\frac{1}{R_g}+\frac{1}{S};$$

where S is the resistance of the shunt, and R_g the resistance of the unshunted galvanometer.

APPENDIX C

TABLES

1. Useful Numbers and Formulas.

$$1 \text{ inch} = 2.5400 \text{ centimetres}$$
$$1 \text{ centimetre} = 0.3937 \text{ inch}$$
$$1 \text{ gramme} = 15.432 \text{ grains}$$
$$1 \text{ gramme} = 0.0353 \text{ ounces avoirdupois}$$
$$1 \text{ ounce avoirdupois} = 28.35 \text{ grammes}$$
$$1 \text{ radian} = 57°.3, \text{ nearly}$$
$$\pi = 3.1416, \text{ nearly}$$
$$\frac{1}{\pi} = 0.3183$$
$$\sqrt{\pi} = 1.7725$$
$$\pi^2 = 9.8696 \ (= 10, \text{ nearly})$$

For a

Circle of radius r, circumference $= 2\pi r$

area $= \pi r^2$

Sphere of radius r, area $= 4\pi r^2$

volume $= \frac{4}{3}\pi r^3$

Cylinder, with circular base of radius r and height h,

volume $= \pi r^2 h$

2. Acceleration of Gravity in Various Localities.

	C. G. S. Units		C. G. S. Units
Boston	980.4	Philadelphia	980.2
Chicago	980.3	New York	980.2
Denver	979.6	San Francisco	979.95
Equator	978.1	St. Louis	979.99
Latitude 45°	980.60	Washington	980.1
Pole	983.1		

Weight of m *grammes* = mg *dynes*

where g denotes the acceleration of gravity.

3. Densities.

Alcohol (absolute) at 20° C.	0.789
Alcohol 95% at 20° C.	0.804
Aluminium (commercial)	2.7–2.8
Brass	8.3–8.7
Copper	8.9
Glass (crown)	2.4–2.7
Glass (flint)	3.1–3.9
Iron (wrought)	7.79–7.85
Iron (cast)	7.0–7.7
Kerosene	0.8
Lead	11.35–11.38
Mercury at 0° C.	13.596
Mercury at 20° C.	13.546
Paraffin	0.88
Platinum	21.5
Porcelain	2.3
Quartz	2.65
Steel	7.6–7.8
Sulphur	2.07
Water at 0° C.	0.99987
Water at 4° C.	1.00000
Water at 19° C.	0.99845
Water at 20° C.	0.99825
Water at 21° C.	0.99804
Water at 22° C.	0.99782
Water at 23° C.	0.99759

4. Coefficient of Sliding Friction.

Brass on cast iron	0.19
Wrought iron on cast iron	0.20
Wrought iron on wrought iron	0.14

Iron on ice (skates)	0.016–0.032
Oak on oak, fibres parallel	0.48
Oak on oak, fibres crossed	0.32
Leather on oak	0.27–0.38
Leather on metals, dry	0.56
Leather on metals, wet	0.36
Leather on metals, oily	0.15

5. Surface Tension of Some Liquids in Contact with Air.

At 20° C.	Dynes per Centimetre
Alcohol	25.5
Mercury	540.
Olive Oil	36.9
Petroleum	31.7
Soap solution (strong)	about 25.
Turpentine	29.7
Water, very pure	81.
Water, ordinary distilled	70–80.

6. Speed of Sound.

	Metres per Second
Air at 0° C.	332
Air at 21° C.	345
Brass	3600
Copper	3600
Glass	5100
Iron	5000
Pine wood	4500
Steel	5100
Water at 4° C.	1399
Water at 25° C.	1457

7. Coefficients of Linear Expansion.

	Between 0° C. and 100° C.
Aluminium	0.000023
Brass	0.000018
Copper	0.000017
Glass	0.0000085
Iron	0.000012
Platinum	0.0000085
Zinc	0.000029

8. Coefficients of Cubical Expansion.

Air, and other gases	0.00367
Glass	0.000025
Mercury	0.00018
Water, between 0° and 20° C.	0.00081
Water, between 0° and 100° C.	0.00043

9. Melting-points.

	In Degrees Centigrade
Glass	800–900
Gold	1035
Ice	0
Iron (cast)	1100–1200
Iron (wrought)	1500–1600
Lead	326
Mercury	— 40
Paraffin	40–58
Sulphur	113
Zinc	415

10. Boiling-points of Water at Various Pressures.

Pressure in Centimetres of Mercury	Boiling-point in Degrees Centigrade	Pressure in Centimetres of Mercury	Boiling-point in Degrees Centigrade
20	66.5	70	97.7
25	71.6	71	98.11
30	75.9	72	98.50
35	79.7	73	98.88
40	83.0	74	99.26
45	86.0	75	99.63
50	88.7	76	100.00
55	91.2	77	100.37
60	93.5	78	100.73
65	95.7		

11. Vapor Pressures at Various Temperatures.

Temperature in Degrees Centigrade	WATER in Centimetres of Mercury	ALCOHOL in Centimetres of Mercury
0°	0.457	1.224
10°	0.914	2.377
20°	1.736	4.400
30°	3.151	7.806
40°	5.487	13.342
50°	9.198	21.982
60°	14.889	35.02
70°	23.331	54.09
80°	35.487	81.18
90°	52.547	118.65
100°	76.000	169.23
110°	107.537	235.98

12. DIMENSIONS, WEIGHT AND RESISTANCE

Gauge No.	Diameter in		Weight	
	Inches	Millimetres	Lbs. per Foot	Lbs. per Ohm
0000	.46	11.684	.640525	13129.29
000	.40964	10.405	.507955	8256.95
00	.3648	9.266	.40284	5193.13
0	.32486	8.254	.319457	3265.84
1	.2893	7.348	.253348	2054.015
2	.25763	6.544	.200915	1291.80
3	.22942	5.827	.159325	812.709
4	.20431	5.189	.126357	522.839
5	.18194	4.621	.10022	321.309
6	.16202	4.115	.0794616	202.062
7	.14428	3.665	.0630134	127.07
8	.12849	3.264	.0499757	79.9258
9	.11443	2.907	.039637	50.2886
10	.10189	2.588	.0314256	31.6036
11	.090742	2.305	.024925	19.882
12	.080808	2.053	.0197665	12.5034
13	.071961	1.828	.0156753	7.86319
14	.064084	1.628	.0124314	4.51033
15	.057068	1.450	.0098584	3.11015
16	.05082	1.291	.0078179	1.95501
17	.045257	1.150	.0062	1.23013
18	.040303	1.024	.004917	.773677
19	.03589	0.899	.0038991	.486524
20	.031961	0.812	.0030922	.305979
21	.028462	0.723	.0024522	.192429
22	.025347	0.644	.0019448	.121037
23	.022571	0.573	.0015421	.076105
24	.0201	0.511	.001223	.0478624
25	.0179	0.455	.0009699	.0301038
26	.01594	0.405	.0007691	.0168719
27	.014195	0.361	.0006099	.0119056
28	.012641	0.321	.0004837	.0074748
29	.011257	0.286	.0003836	.0047087
30	.010025	0.255	.0003042	.0029617
31	.008928	0.227	.0002413	.0018306
32	.00795	0.202	.0001913	.00117133
33	.00708	0.180	.0001517	.00073678
34	.006304	0.160	.0001203	.0004631
35	.005614	0.143	.0000954	.000291272
36	.005	0.127	.00007568	.000183269
37	.004453	0.113	.00006003	.000115298
38	.003965	0.101	.00004759	.000072474
39	.003531	0.090	.00003774	.000045582
40	.003144	0.080	.00002992	.000036980

OF BARE COPPER WIRE — AMERICAN GAUGE

Length — Feet		Resistance — Ohms		Gauge No.
Per Lb.	Per Ohm	Per Foot	Per Lb.	
1.56122	20497.7	.00004878	.00007616	0000
1.9687	16255.27	.00006151	.00012111	000
2.4824	12891.37	.00007757	.00019256	00
3.1303	10223.08	.00009781	.0003062	0
3.94714	8107.49	.00012334	.00047686	1
4.97722	6429.58	.00015553	.00077411	2
6.2765	5098.61	.00019613	.00123102	3
7.9141	4043.6	.0002473	.00191263	4
9.97983	3206.61	.00031185	.00311227	5
12.5847	2542.89	.00039325	.00494898	6
15.8696	2015.51	.0004959	.00785156	7
20.0097	1599.3	.00062527	.0125116	8
25.229	1268.44	.00078837	.0198852	9
31.8212	1055.66	.00099437	.031642	10
40.1202	797.649	.0012537	.0502987	11
50.5906	632.555	.0015809	.0799783	12
63.7948	501.63	.0019935	.127172	13
80.4415	397.822	.0025137	.221713	14
101.4365	315.482	.0031697	.321528	15
127.12	250.184	.003997	.511504	16
161.29	198.409	.0050401	.812918	17
203.374	157.35	.0063553	1.29253	18
256.468	124.777	.0080142	2.0554	19
323.399	98.9533	.0101058	3.2682	20
407.815	78.473	.0127432	5.19671	21
514.193	62.236	.0160678	8.26197	22
648.452	49.3504	.0202633	13.13974	23
817.688	39.1365	.0255516	20.89323	24
1031.038	31.0381	.0322184	33.2184	25
1300.180	24.6131	.0406288	53.8247	26
1639.49	19.5191	.0512318	83.994	27
2067.36	15.4793	.0646023	133.5563	28
2606.95	12.2854	.081464	212.373	29
3287.08	9.7355	.102717	337.639	30
4414.49	7.72143	.12951	536.7515	31
5226.91	6.12243	.163334	853.732	32
6590.41	4.85575	.205942	1357.241	33
8312.8	3.84966	.25976	2159.361	34
10481.77	3.05305	.327541	3433.21	35
13214.16	2.4217	.41293	5456.45	36
16659.97	1.92086	.520601	8673.2	37
21013.25	1.52292	.656635	13798.04	38
26496.23	1.20777	.82797	21938.11	39
33420.63	0.97984	1.04435	27041.4	40

13. Additional Data concerning Heat.

Heat of fusion of ice . . .	79.4 calories per gramme
Heat of evaporation of water .	536. calories per gramme
Heat of evaporation of ether (15° C.)	89. calories per gramme

Mechanical equivalent of 1 gramme of water heated 1° C.
= 424 metre-grammes.

Mechanical equivalent of 1 lb. of water heated 1° F.
= 772 foot-pounds.

14. Electrical Conductivities, Relative.

Silver	1 000 000 000.
Mercury	16 000 000.
Gas carbon	400 000.
Dilute sulphuric acid . .	160.
Gutta percha . . .	0.000 000 000 004

15. Resistances of Some Metals.

Substance	Resistance in ohms of a circular wire one metre in length and one millimetre in diameter	Resistance in ohms of a wire one centimetre long and one square centimetre in cross-section
Aluminium . .	0.377	3.0×10^{-6}
Brass, soft . .	0.867	6.9×10^{-6}
Copper . . .	0.2136 – 0.2764	$1.7 - 2.2 \times 10^{-6}$
German silver . .	2.965	23.6×10^{-6}
Iron, soft . . .	1.395	11.1×10^{-6}
Mercury . . .	11.85	94.3×10^{-6}
Platinum . . .	1.696	13.5×10^{-6}
Silver, soft . .	0.189	1.5×10^{-6}
Zinc	0.741	5.9×10^{-6}

16. Indices of Refraction for Sodium Light.

Air	1.00029
Carbon bisulphide	1.63
Diamond	2.47
Fluorspar	1.434
Glass (crown)	1.51–1.61
Glass (flint)	1.54–1.75
Quartz	1.55
Rock salt	1.544
Water	1.33

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